Shedding light
to the dark side of the Universe

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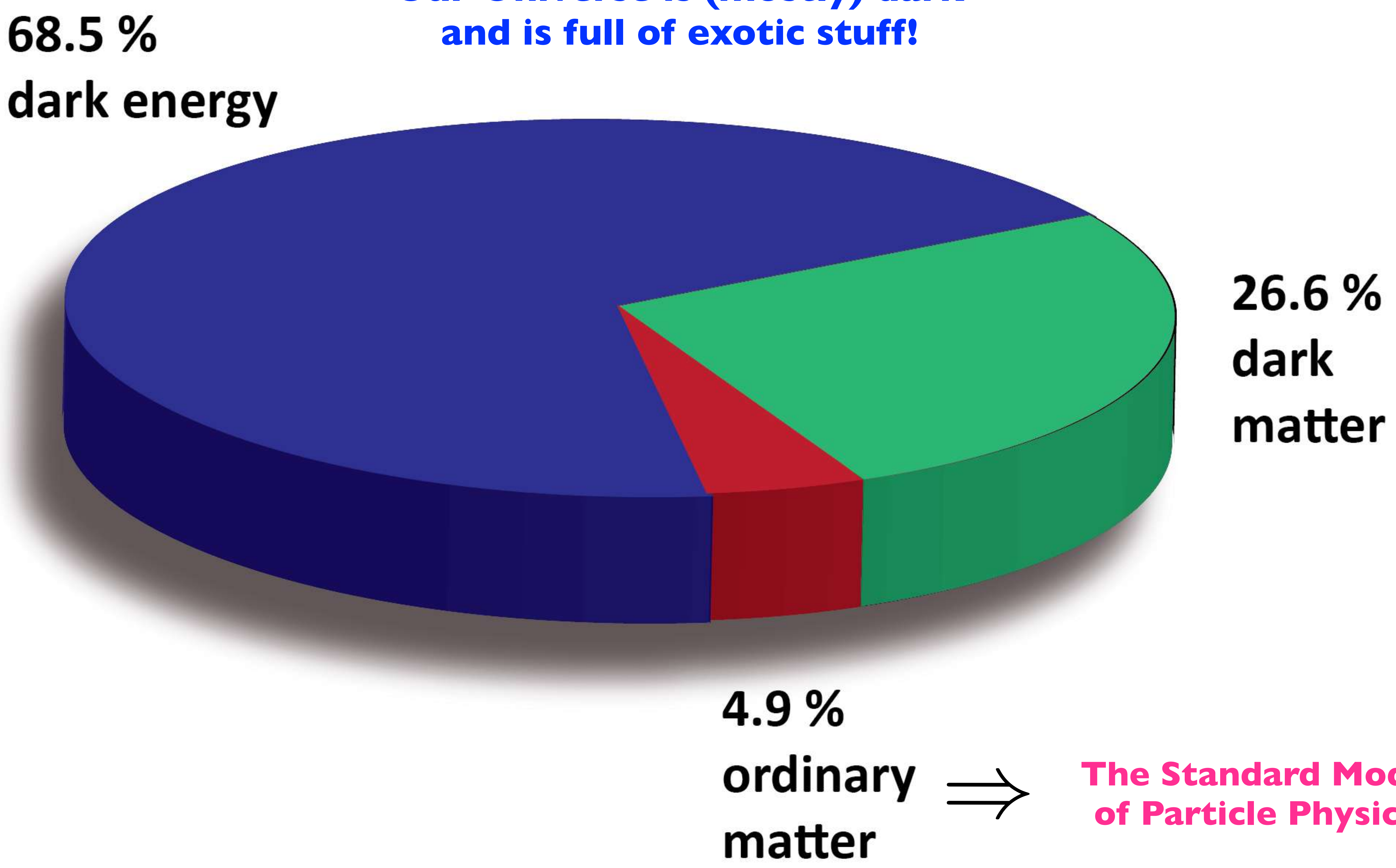
Pie chart of the Universe

Our Universe is (mostly) dark and is full of exotic stuff!



$\Longrightarrow$ **The Standard Model of Particle Physics!**

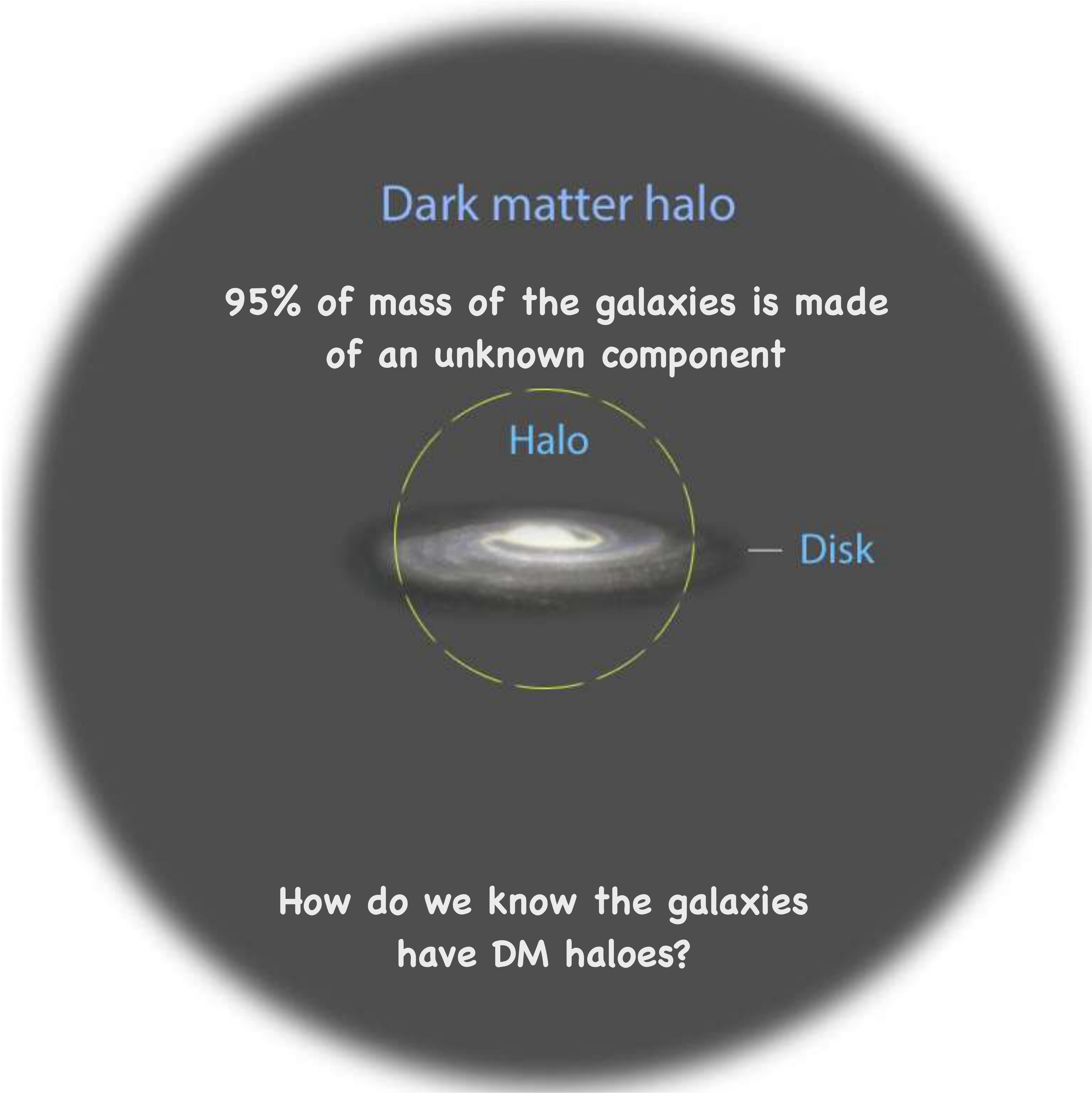
Our job is to figure out what the rest is!

How do we know about the existence of Dark Matter?

Dark Matter is the bulk of the mass in galaxies and clusters!

Observational evidence:

- ✓ rotation curves
- ✓ gravitational lensing
- ✓ hot gas in clusters
- ✓ the Bullet Cluster



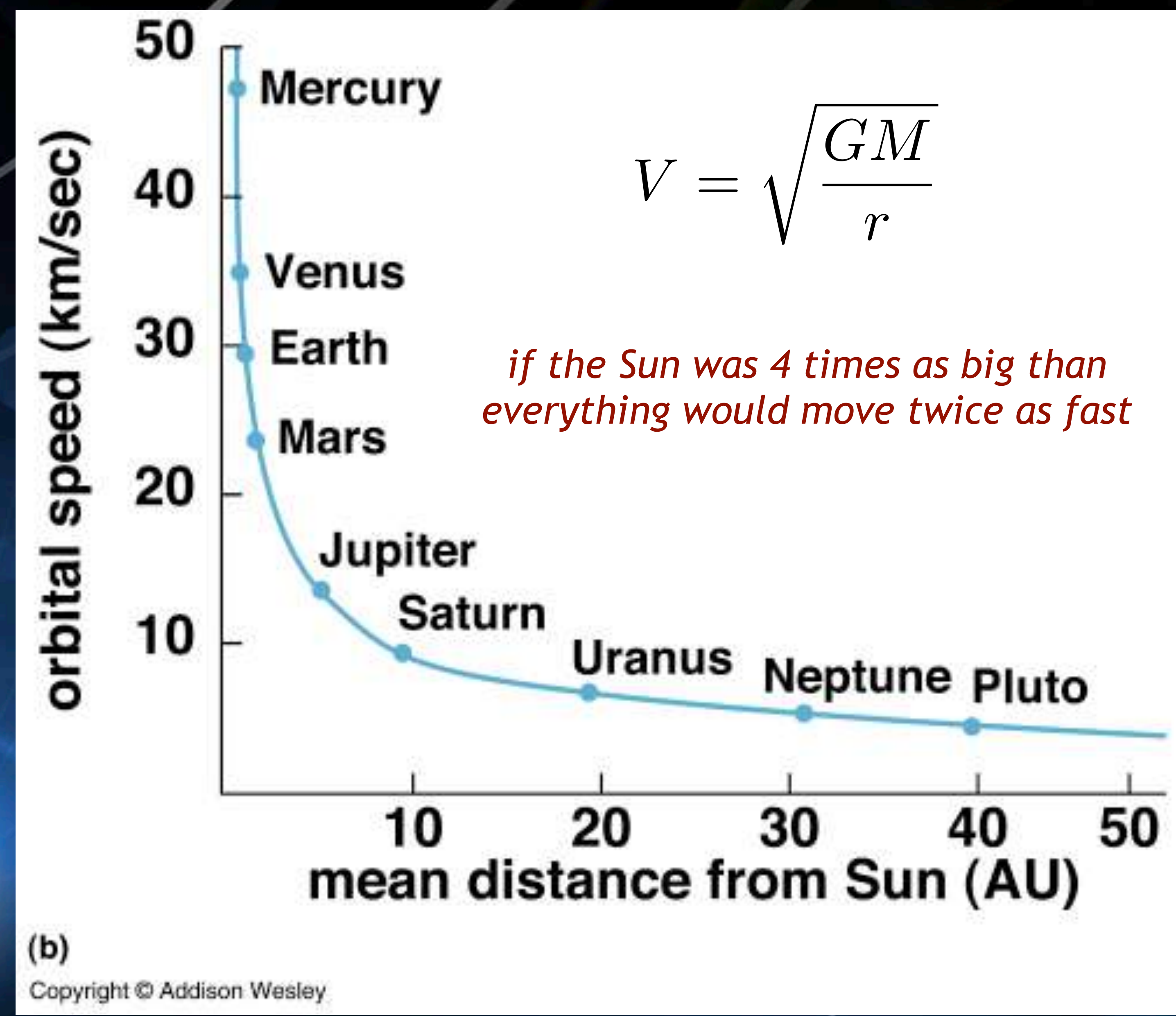
95% of mass of the galaxies is made of an unknown component

How do we know the galaxies have DM haloes?

https://www.physik.uzh.ch/groups/serra/NewPhysics.html

Solar System rotation curve

...that is how fast you move
as you move further out from the centre
(Tyco Brage's measurements of orbits)

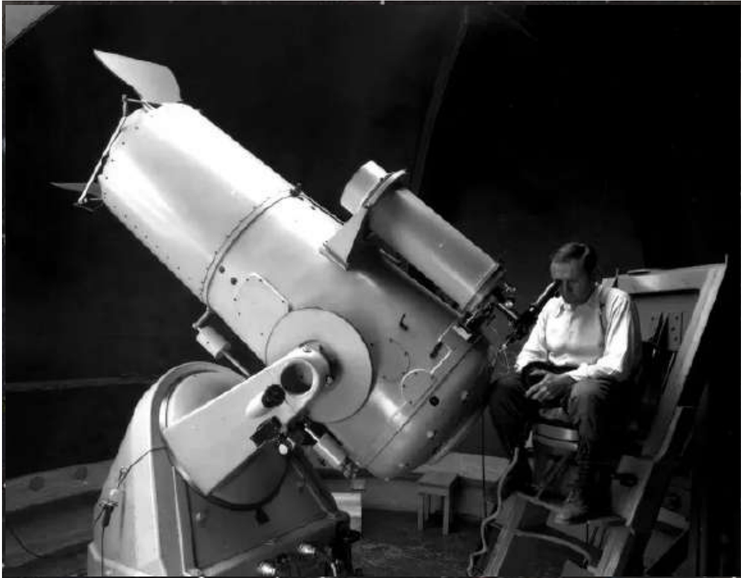


$$V = \sqrt{\frac{GM}{r}}$$

if the Sun was 4 times as big than everything would move twice as fast

An analogy with the Solar system gives a good example of how we look for those dark objects

The Coma Cluster: 1000's of galaxies



Why Coma is still there?

not enough stellar material to keep galaxies together at such speeds

Zwicky proposed "Dunkle Materie" as the explanation

Zwicky in 1930's studied motion of galaxies in the Coma cluster and found that some of them are moving way too fast (1000 km/sec) to remain bounded by Coma's gravitational field

It's not stars, it doesn't shine, it's dark, It's MYSTERIOUS!

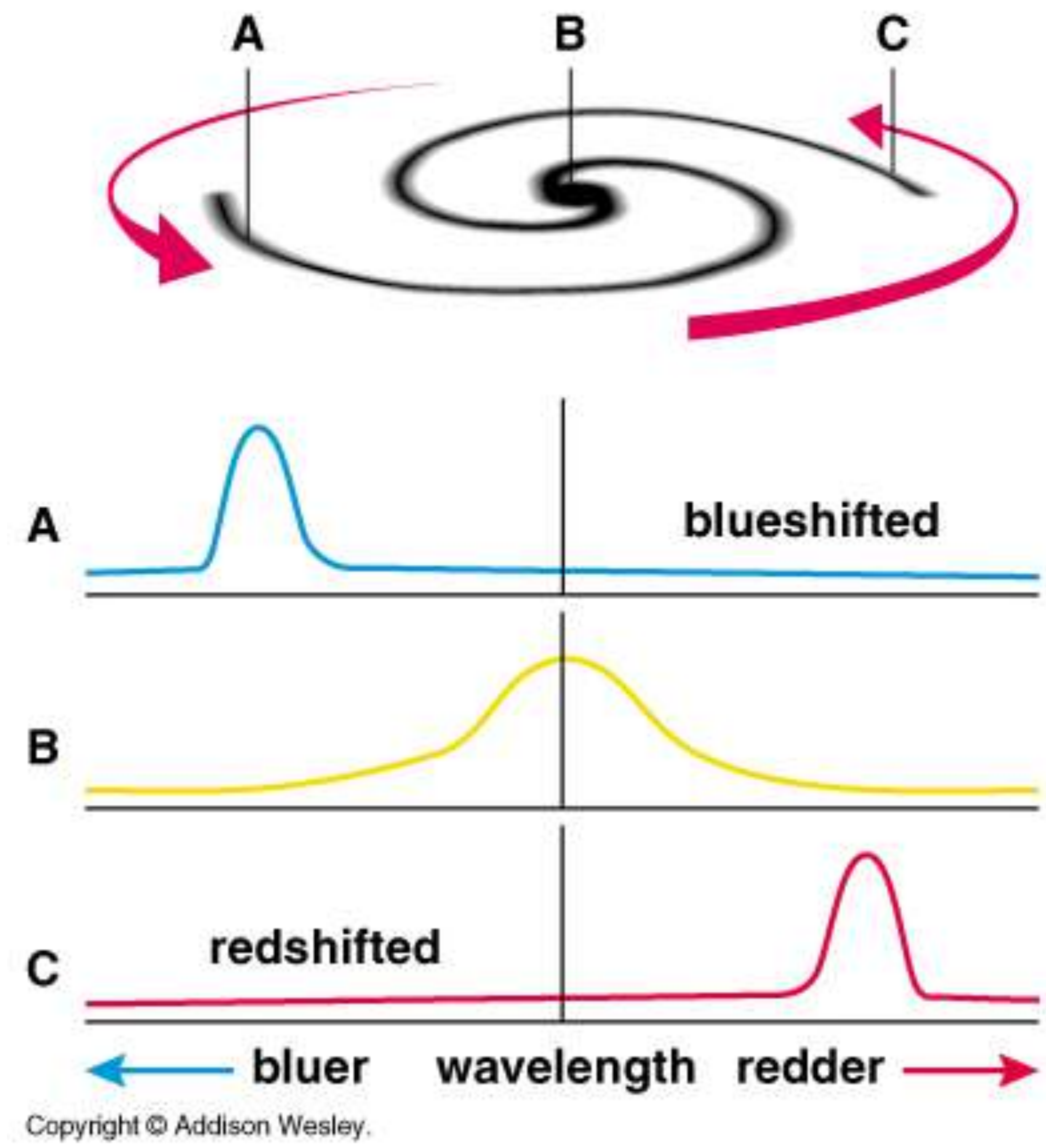
The Coma Cluster that marked the discovery of Dark Matter. Credits: Dan Watt

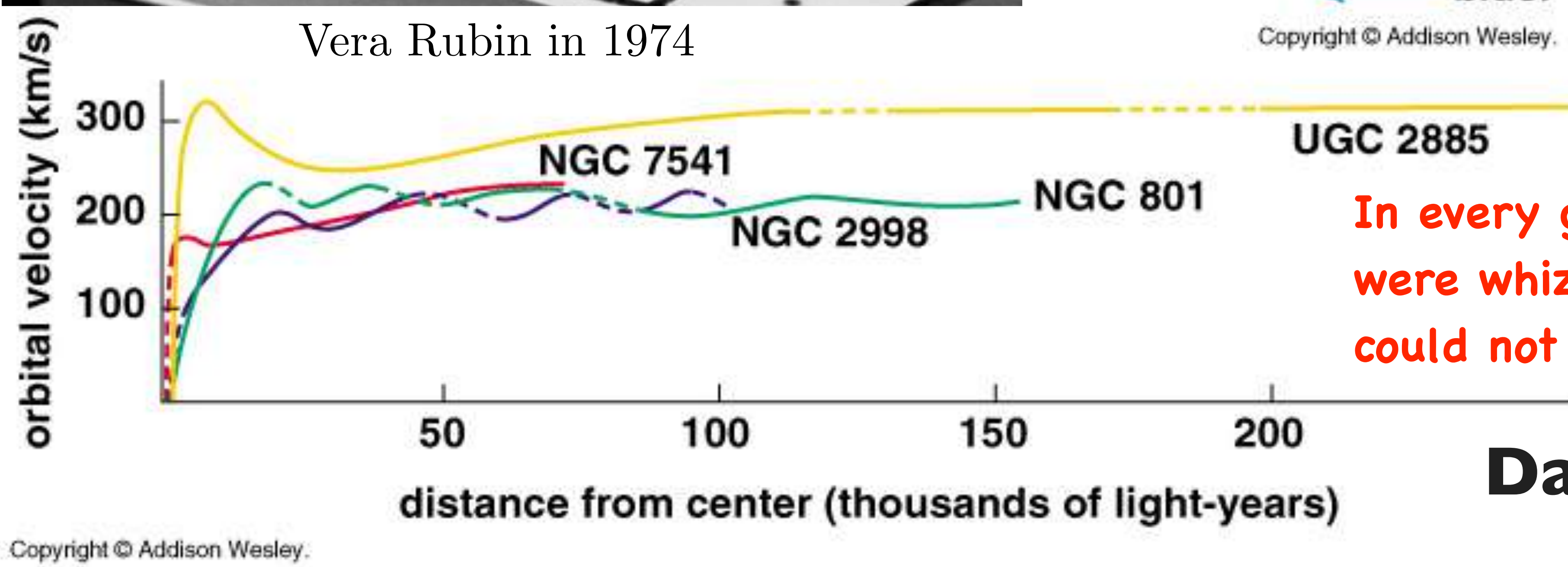
three years before Zwicky, a Swedish scientist Knut Lundmark had made the same kind of observations and in fact got mass of one of our neighbouring galaxies almost correctly spot on!

Mother of Dark Matter

Vera Rubin in 1974

work by Vera Rubin and collaborators in 1970's that nailed it down that DM has to exist!



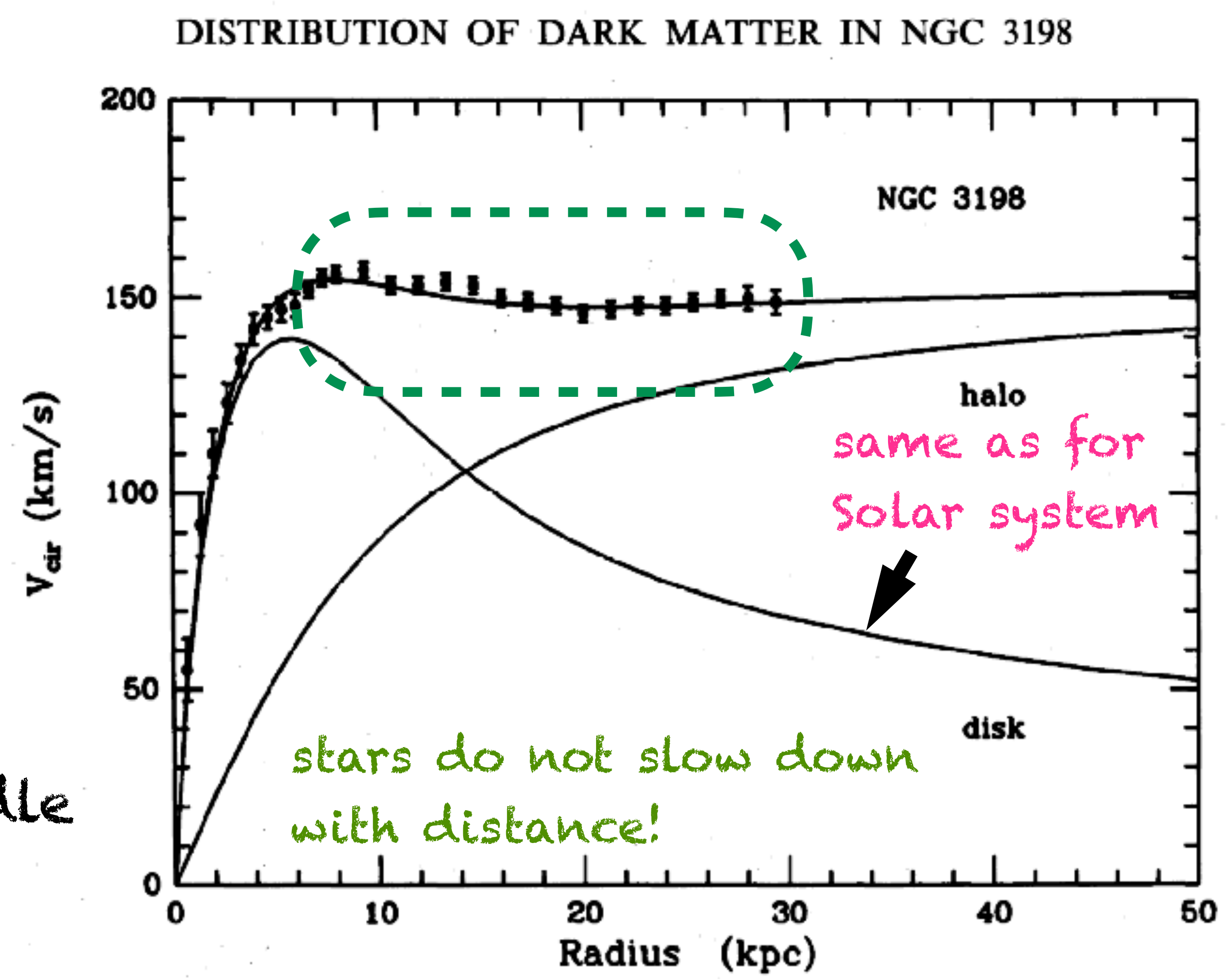


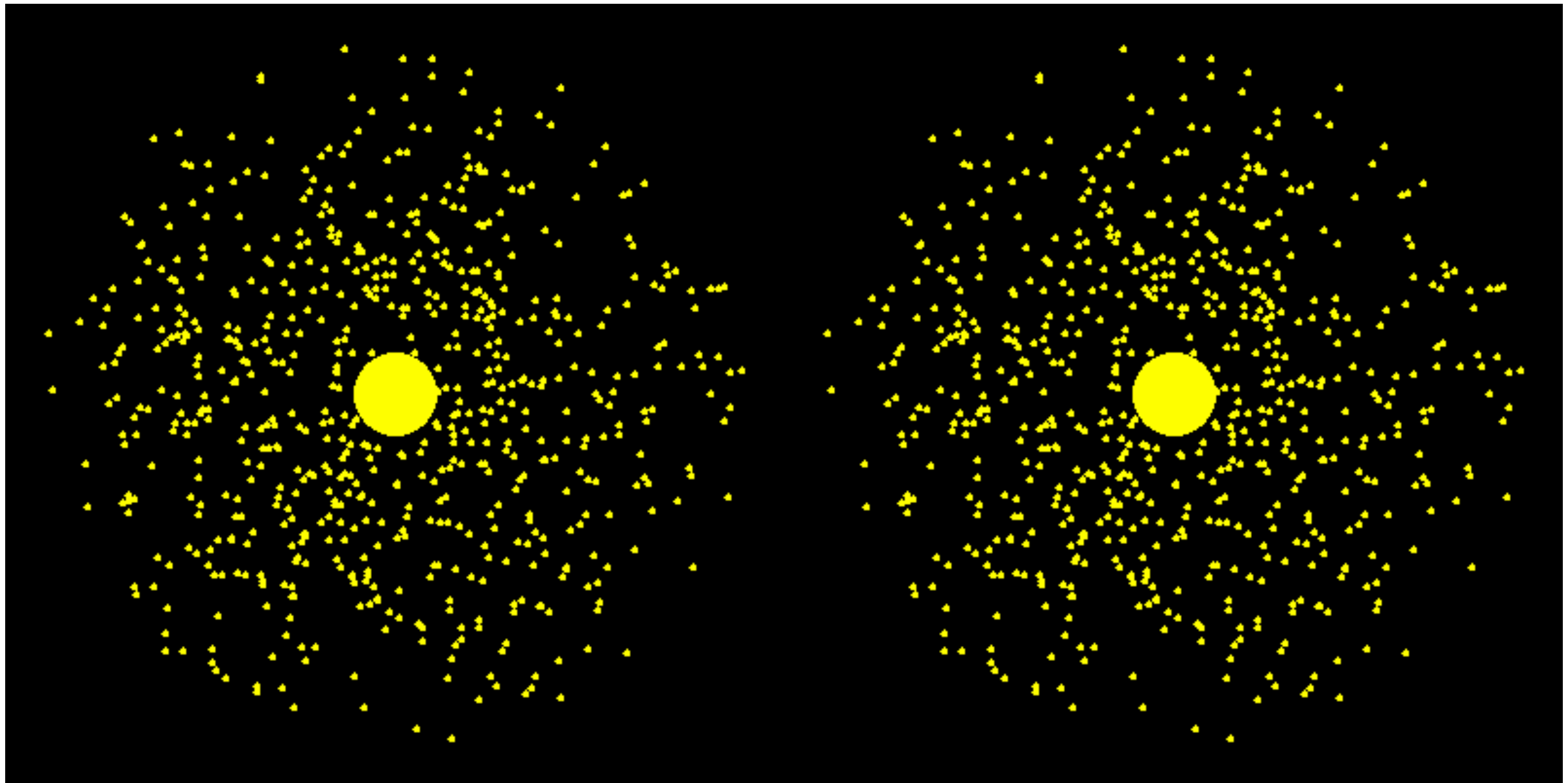
In every galaxy they looked at, things were whizzing around too rapidly, and they could not explain that!

Dark Matter problem

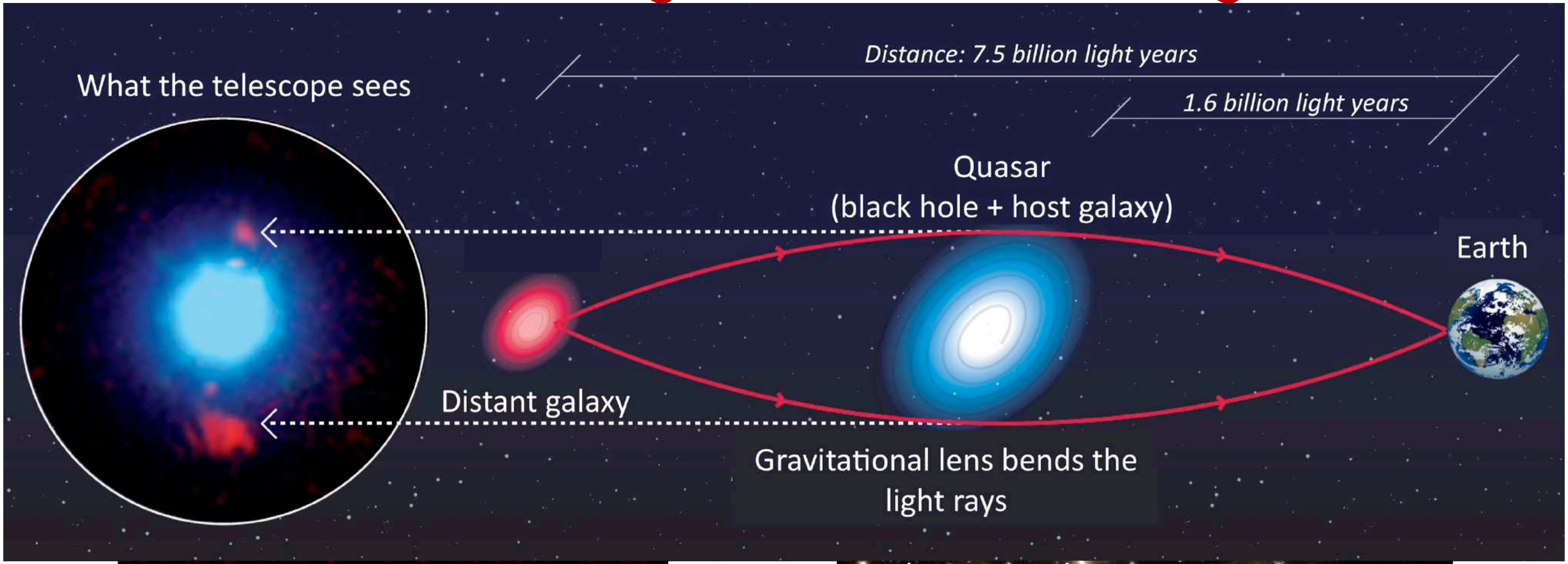
Galactic rotation curve

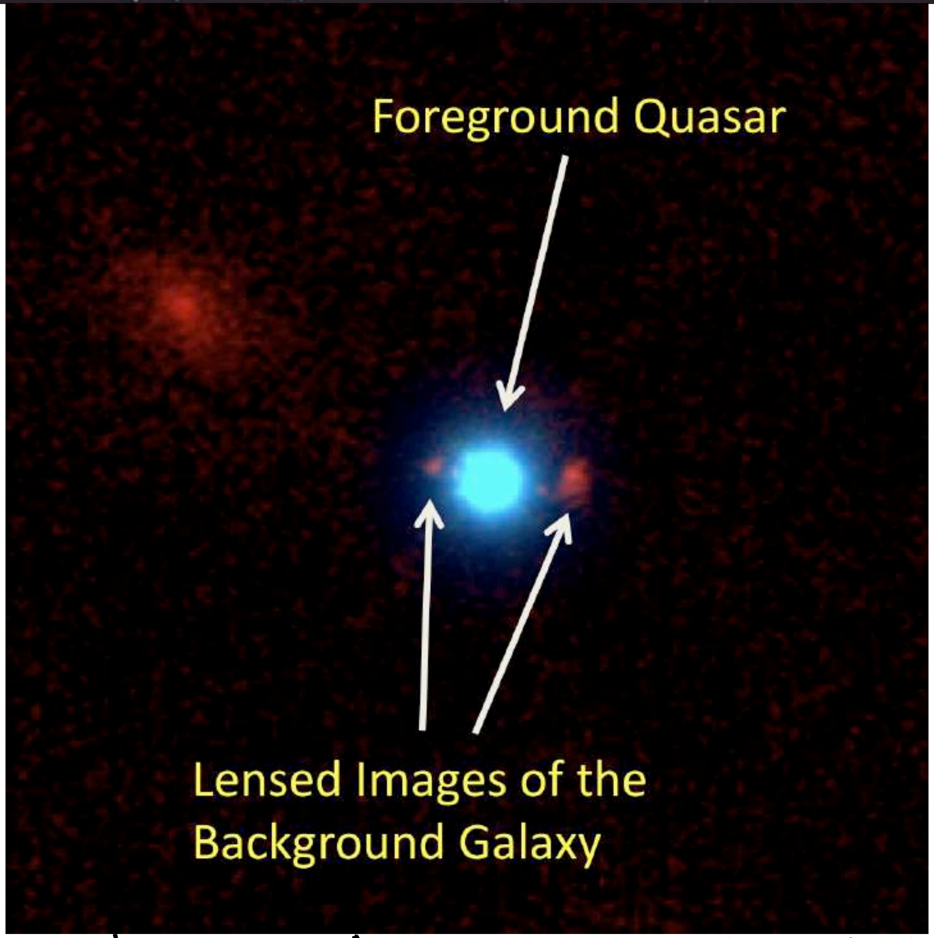
- ✓ watch stars and gas moving around in the middle
- ✓ the speeds of those objects in an orbit here are determined by how much there is mass there in the middle
- ✓ If there is more mass in the middle than these things move faster





Mass bends light! Einstein's lensing





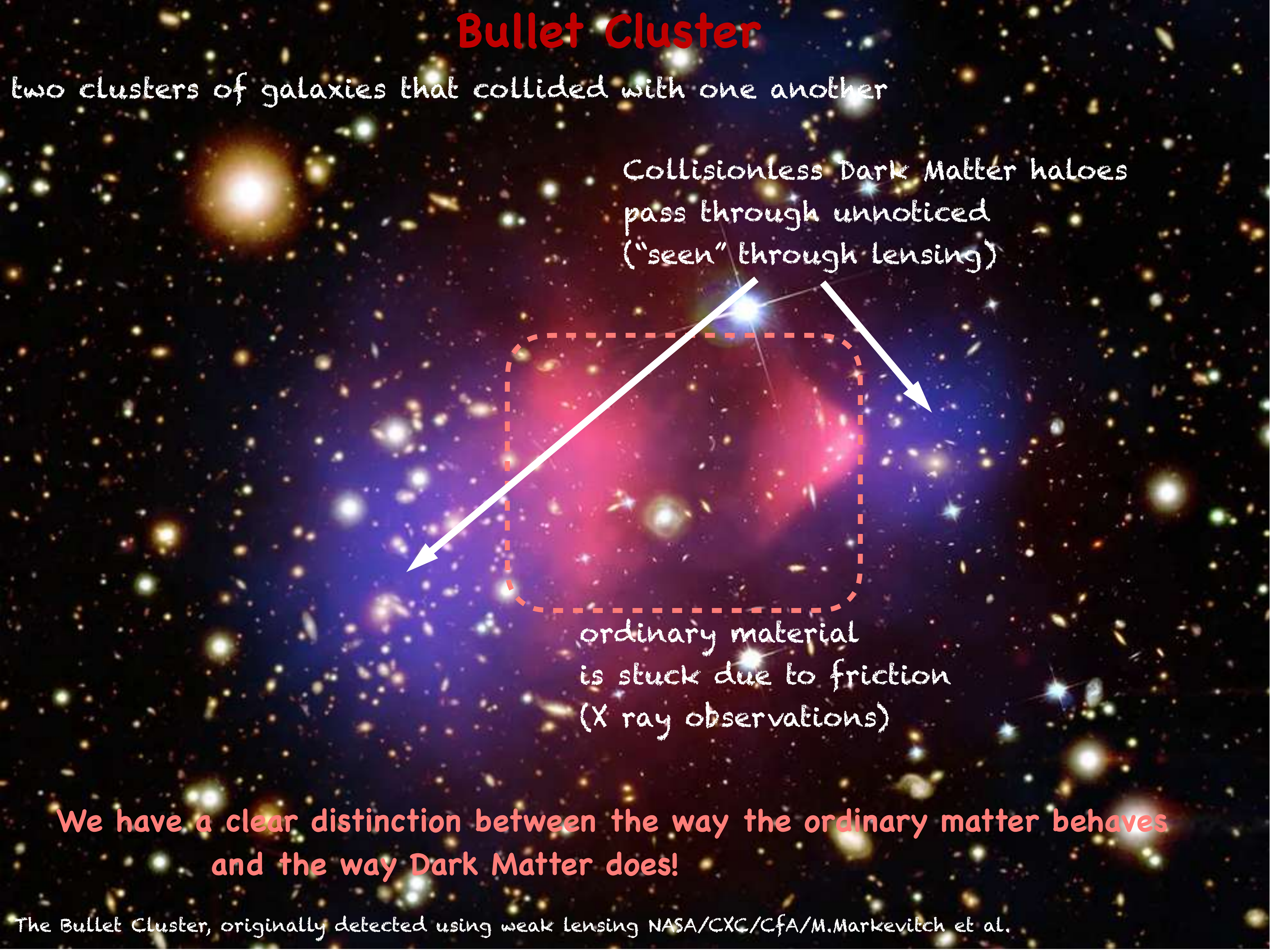
Credit: F. Courbin, S. G. Djorgovski, G. Meylan, et al., Caltech / EPFL / WMKO

When you reconstruct how much mass there is between the distant galaxy and us, you get pictures like this

Mass distribution of CL0024 (courtesy of Tony Tyson, Lucent Technologies)

Bullet Cluster

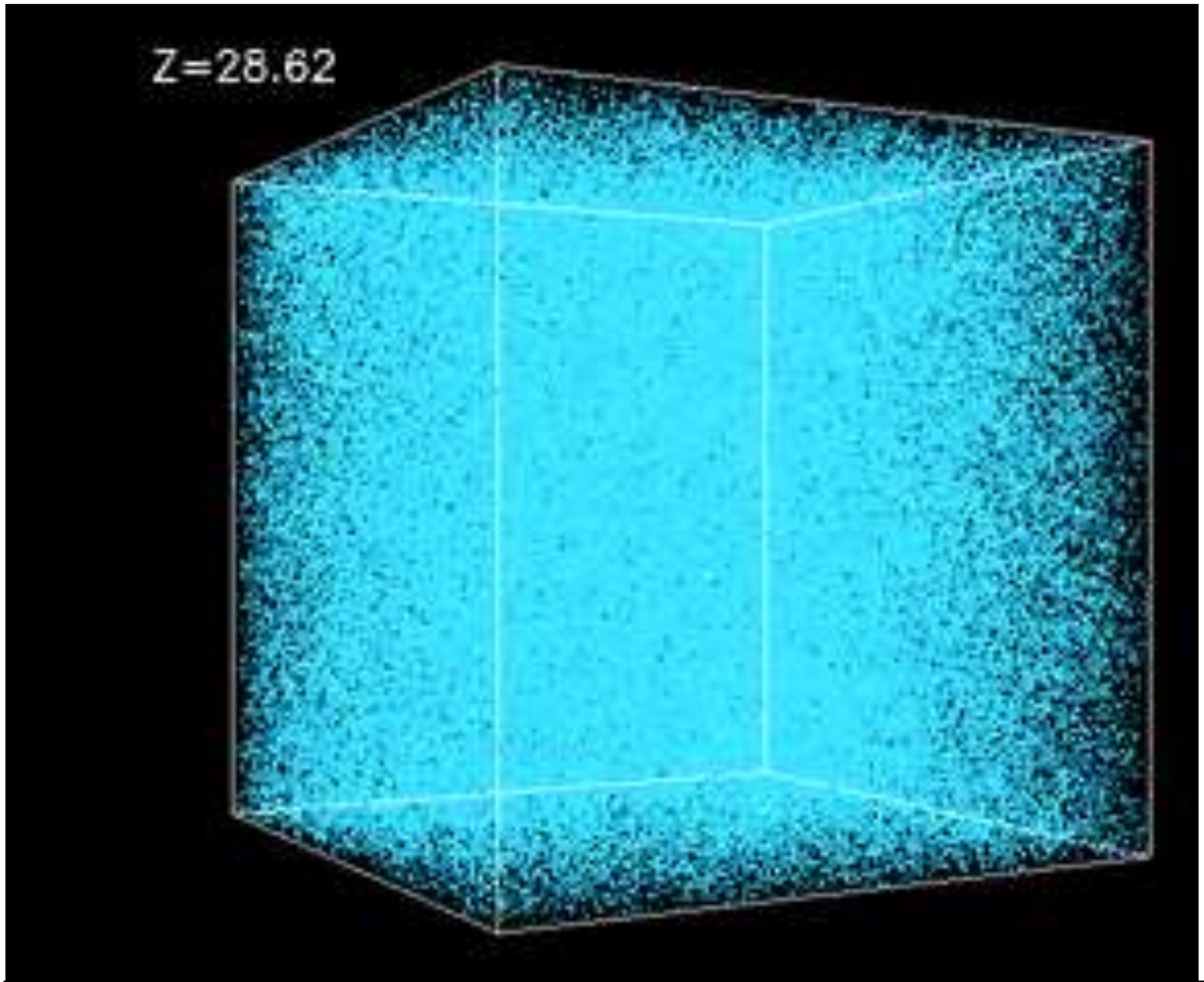
two clusters of galaxies that collided with one another



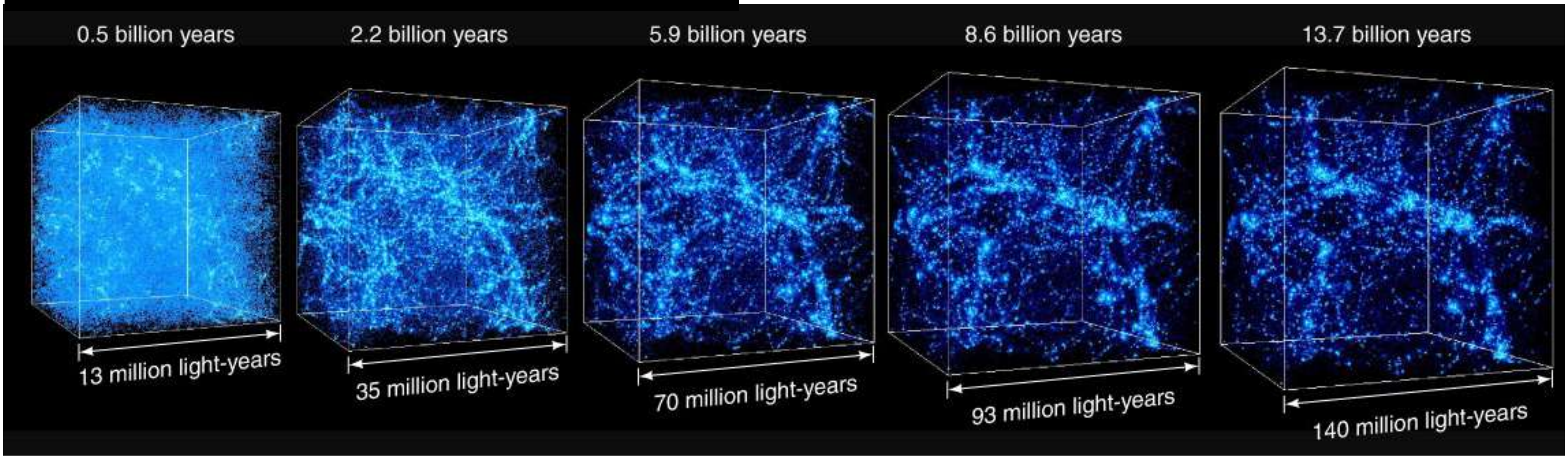
We have a clear distinction between the way the ordinary matter behaves and the way Dark Matter does!

The Bullet Cluster, originally detected using weak lensing NASA/CXC/CfA/M.Markevitch et al.

Dark Matter in Large Scale Structure (LSS) formation



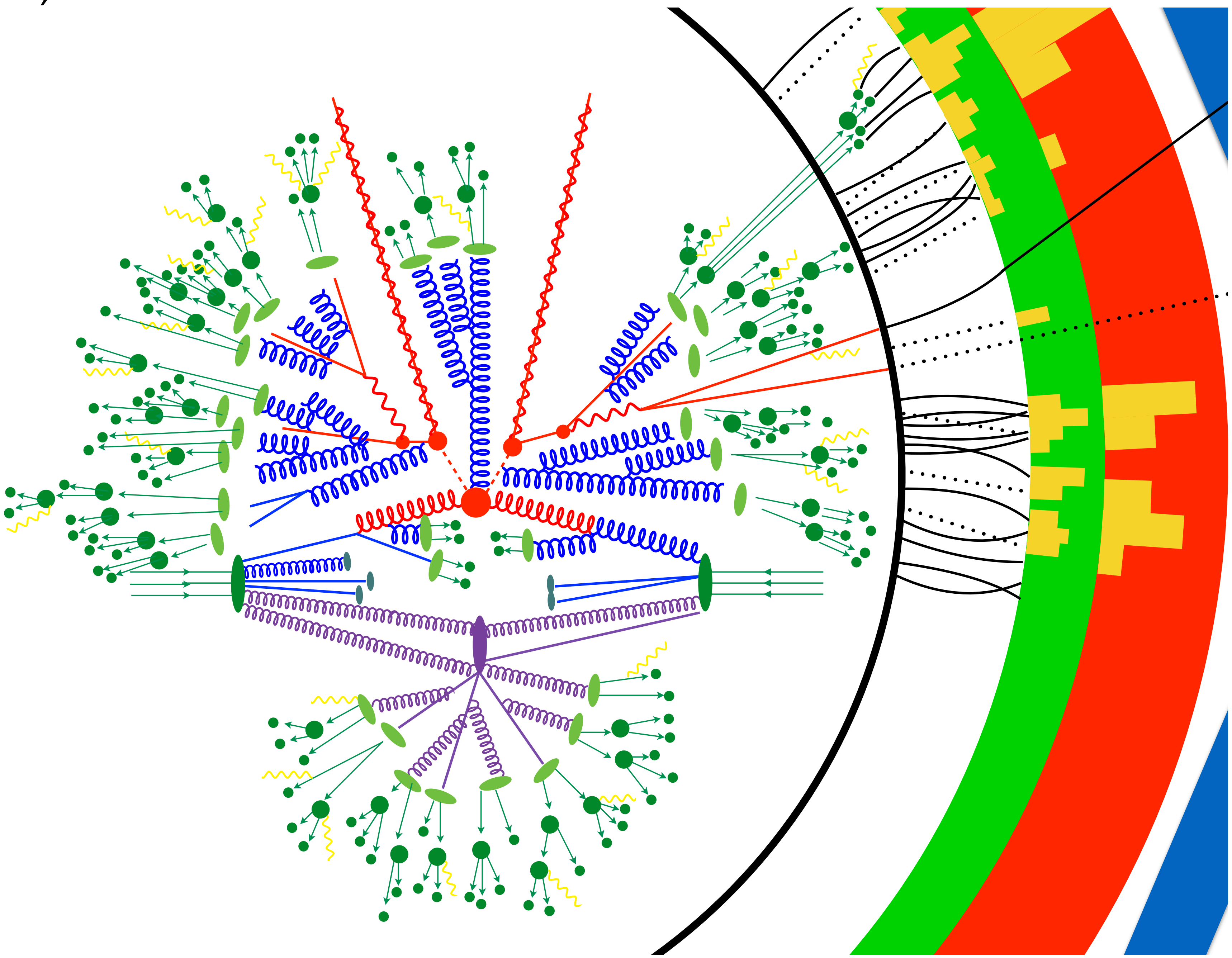
- ✓ initial conditions from inflation (uniform matter distribution in early U.)
- ✓ Dark Matter particles (in blue) come together to make galaxies, clusters (Cosmic Web of LSS)
- ✓ The overdense regions accrete more mass and grow, less dense regions become voids
- ✓ Ordinary atoms talk to light that streams out pulling out any clustering of matter
- ✓ Computer simulations with Dark Matter match the data (long filaments of clusters)



Without Dark Matter we would not be able to exist!

How do we look for Dark Matter in laboratory?

Microscopic physics (particle interactions, scattering…) ⇒ Large-distance phenomena (hadronisation, propagation, jets…) ⇒ Detector response



Particle colliders are the world's best microscopes!

BUT! no hints of Dark Matter particle yet!

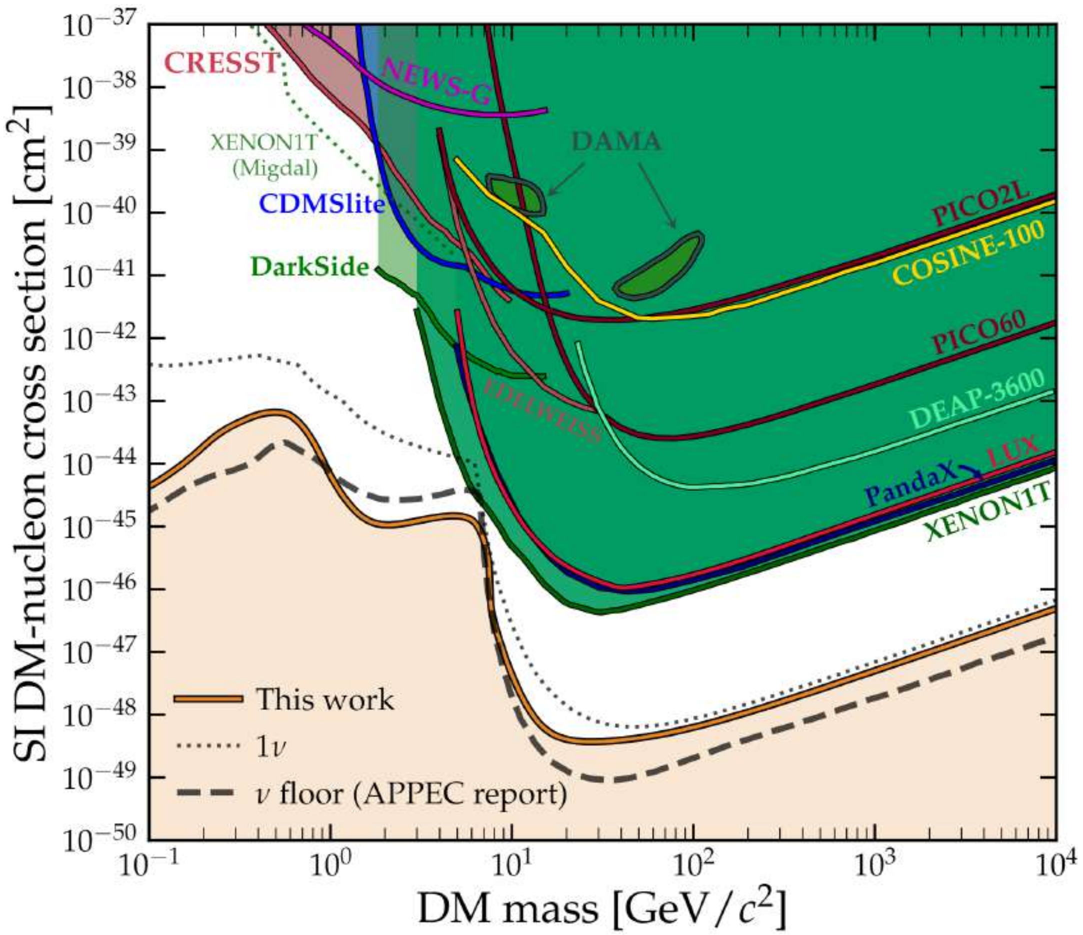
Squeezing the ``WIMP miracle´´

Natural WIMP relic abundance determined by weak-scale and weak-coupling:

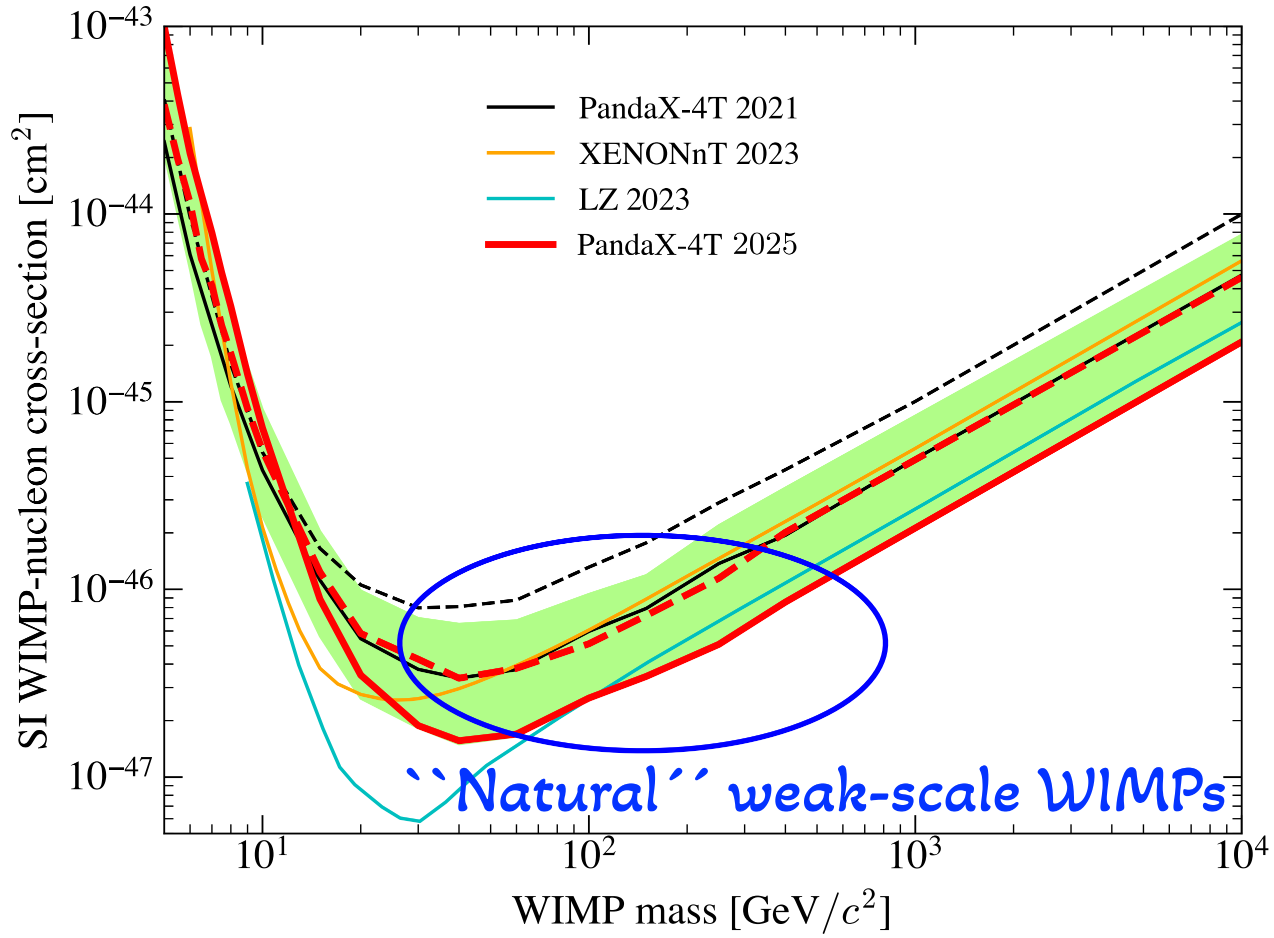
$$\Omega h^2 \simeq 0.12 \times \left(\frac{3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma v \rangle} \right)$$

BUT! Null results from Direct Detection measurements so far!

O'Hare, PRL 127, 251802 (2021)

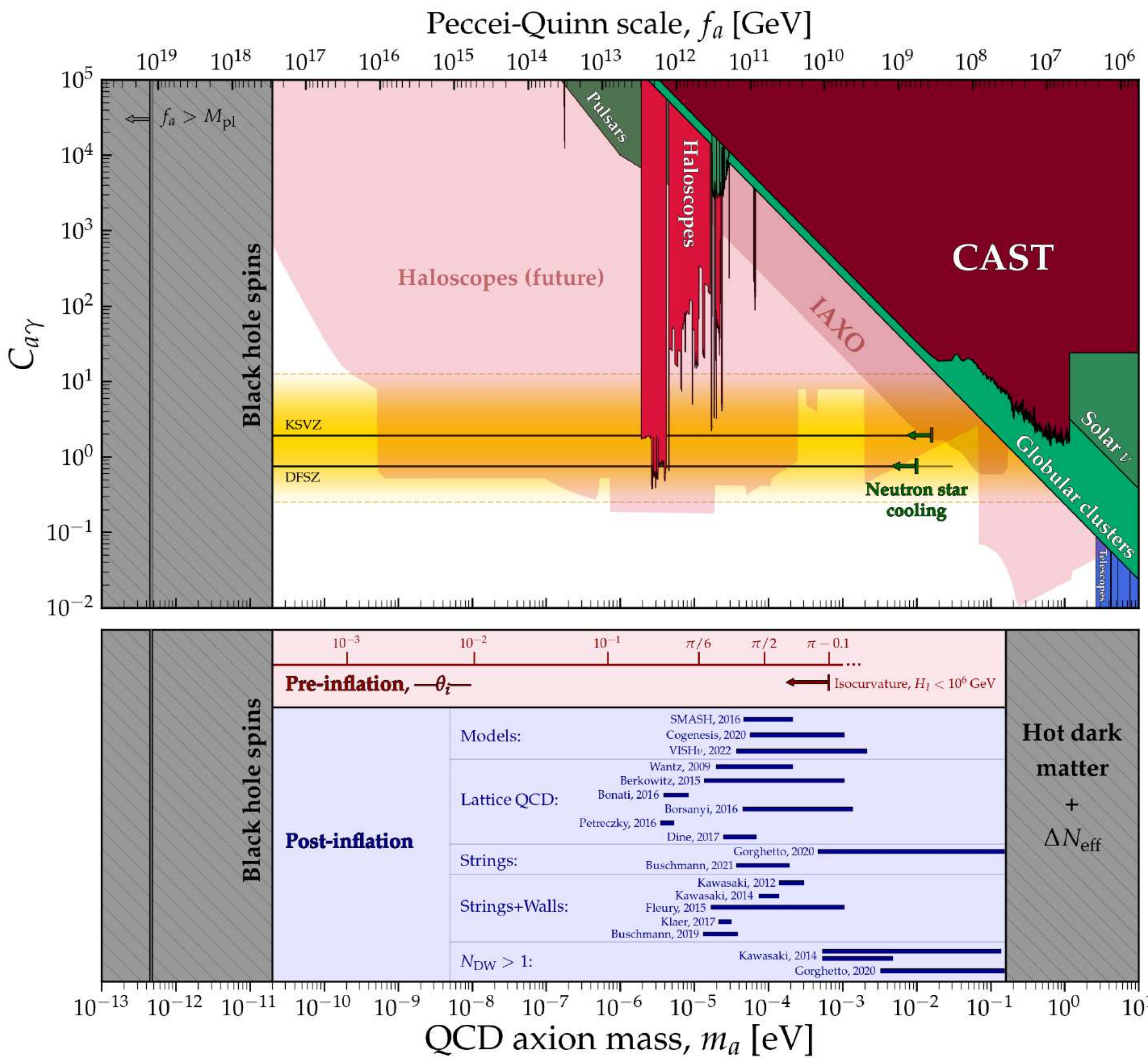


PandaX Collaboration, PRL 134, 011805 (2025)



Other particle candidates: Axions

F. Chadha-Day et al., Sci. Adv. 8 (2022) no.8

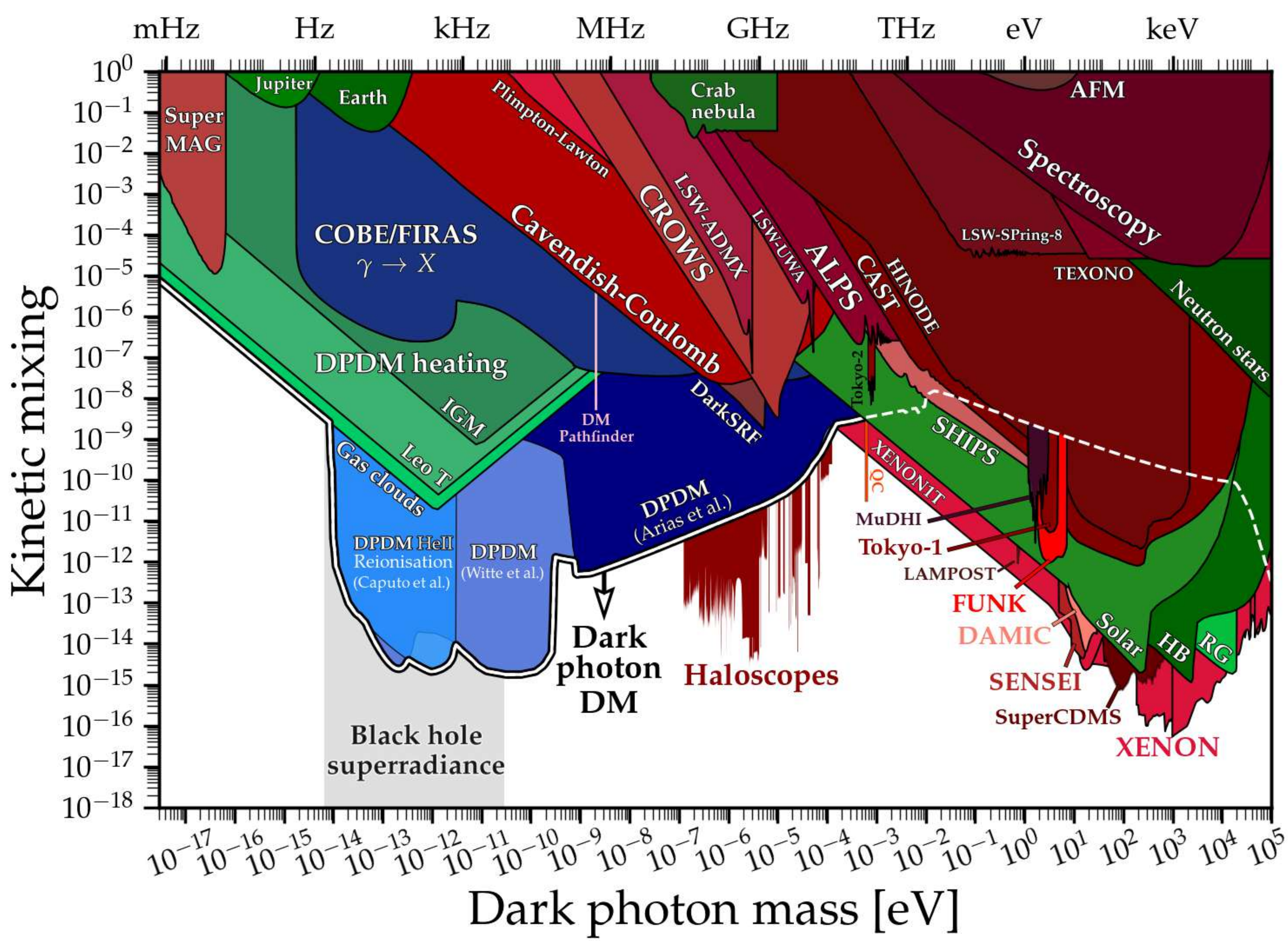


Other particle candidates: Dark Photons

Kinetically mix with electromagnetism:

A. Caputo et al., PRD 104, 095029 (2021)

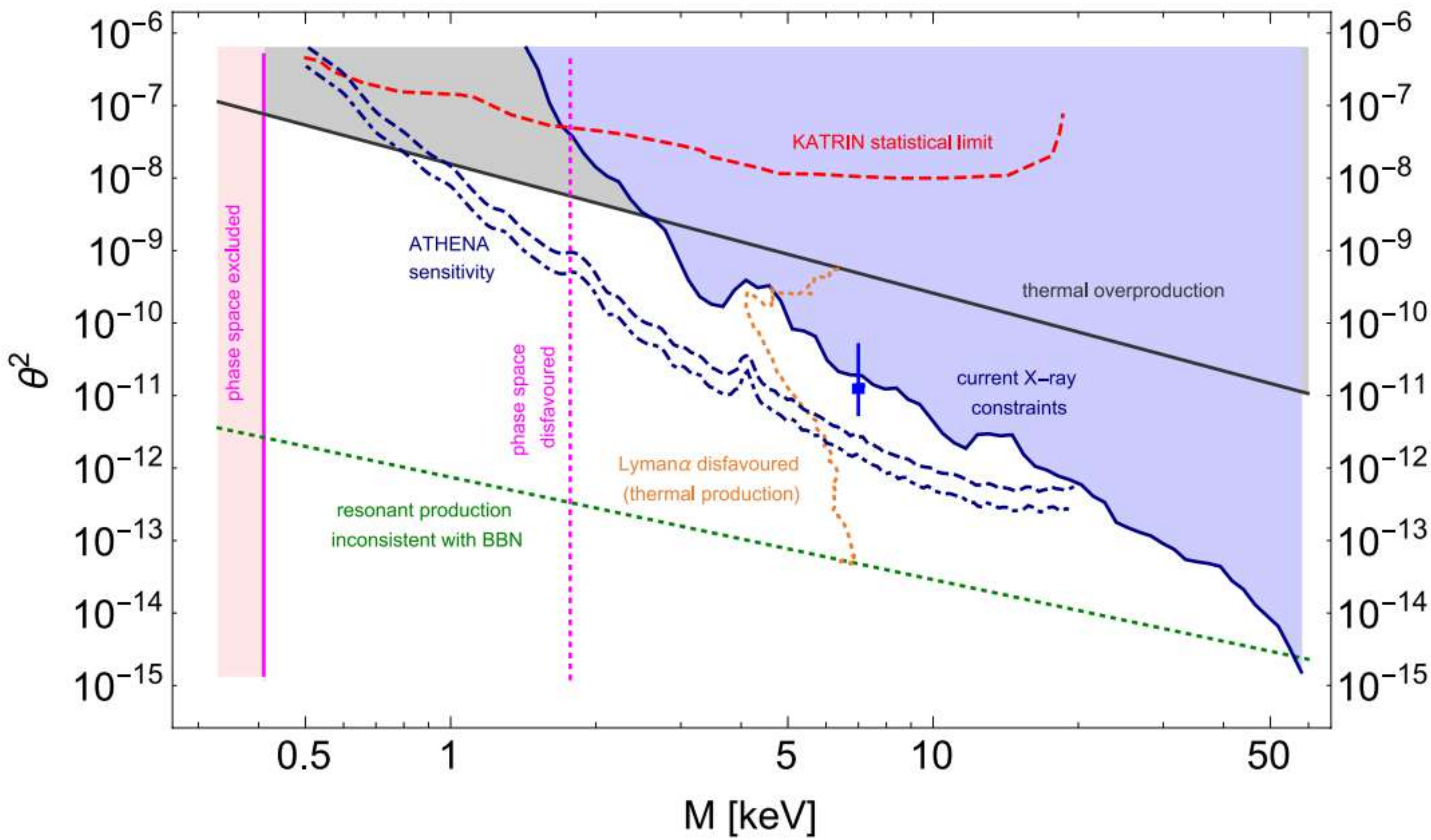
$$\mathcal{L} = -\frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$



Other particle candidates: Sterile neutrinos

Mix with active neutrinos…

A. Boyarsky et al., Prog. Part. Nucl. Phys. 104 (2019)



Strongly coupled dynamics and Dark Matter

- Important physical examples of gauge fields are realised in Nature:
  QCD and electroweak interactions

- Non-perturbative QCD phenomena are far from being understood:
  quark confinement, mass gap, QCD phase transitions,
  hot/dense QCD phenomena etc

- Non-abelian gauge (Yang-Mills) fields are present in most of
  UV completions of the Standard Model:
  GUTs, string/EDs compactifications etc

- Confining hidden Yang-Mills sectors are often considered as a plausible
  source of Dark Matter in the Universe:
  dark scalar/vector glueballs, dark pions, dark baryons etc

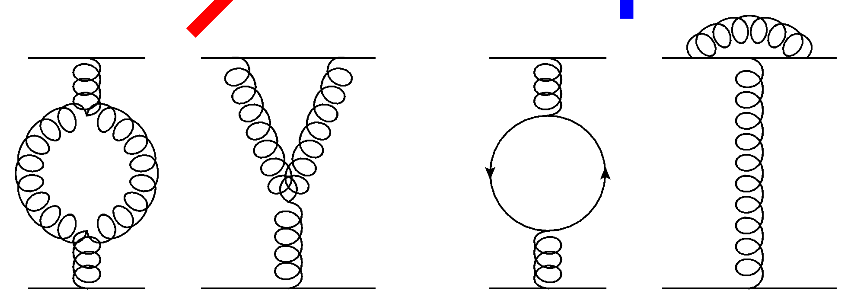
- Particular focus here:
  on non-perturbative confining dynamics in cosmology: glueball abundance
  in the Universe
  and searches for Dark Matter:
  prospects and challenges of direct detection or "dark gluonic composites"

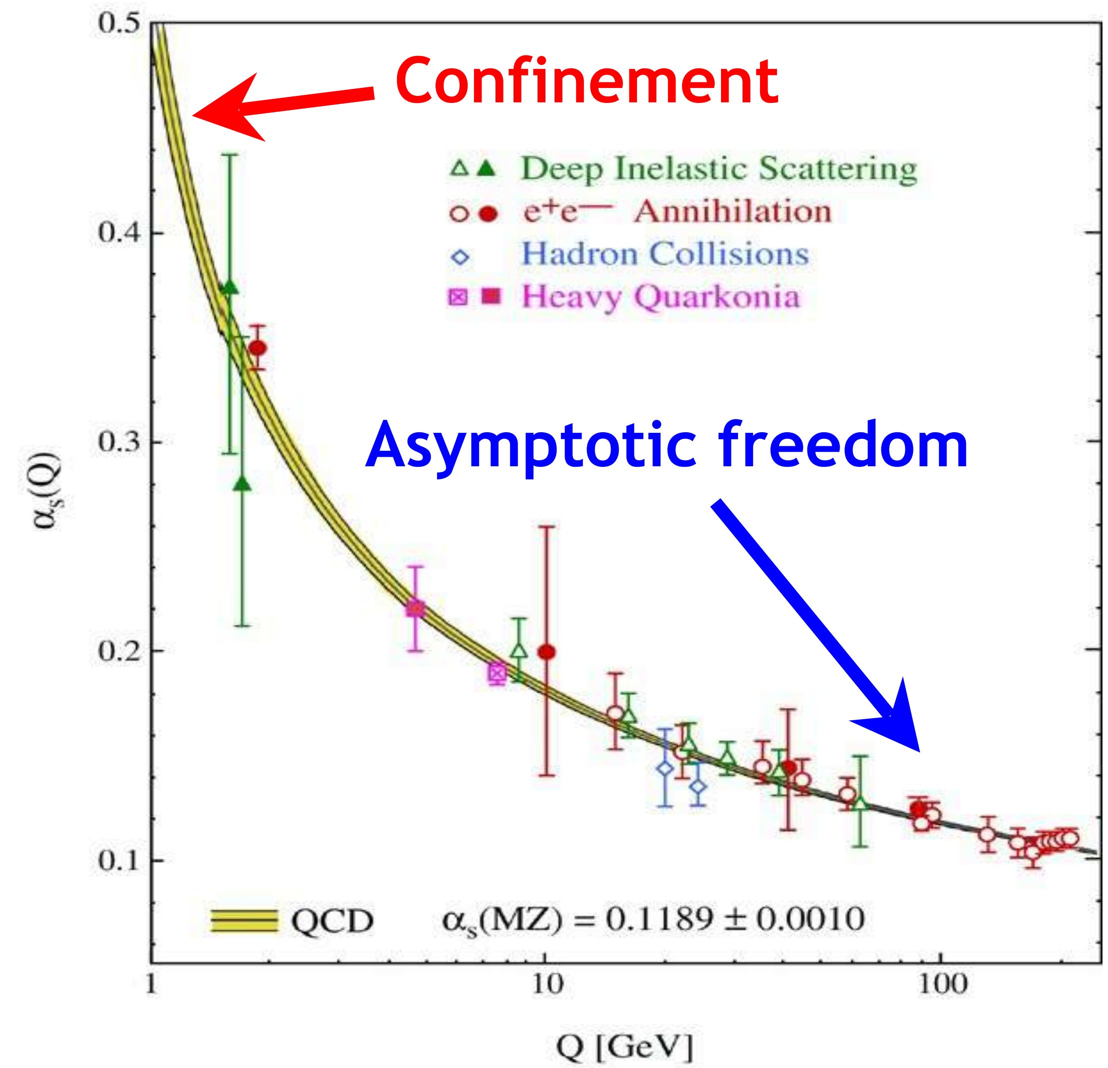
Confining gauge theory of QCD

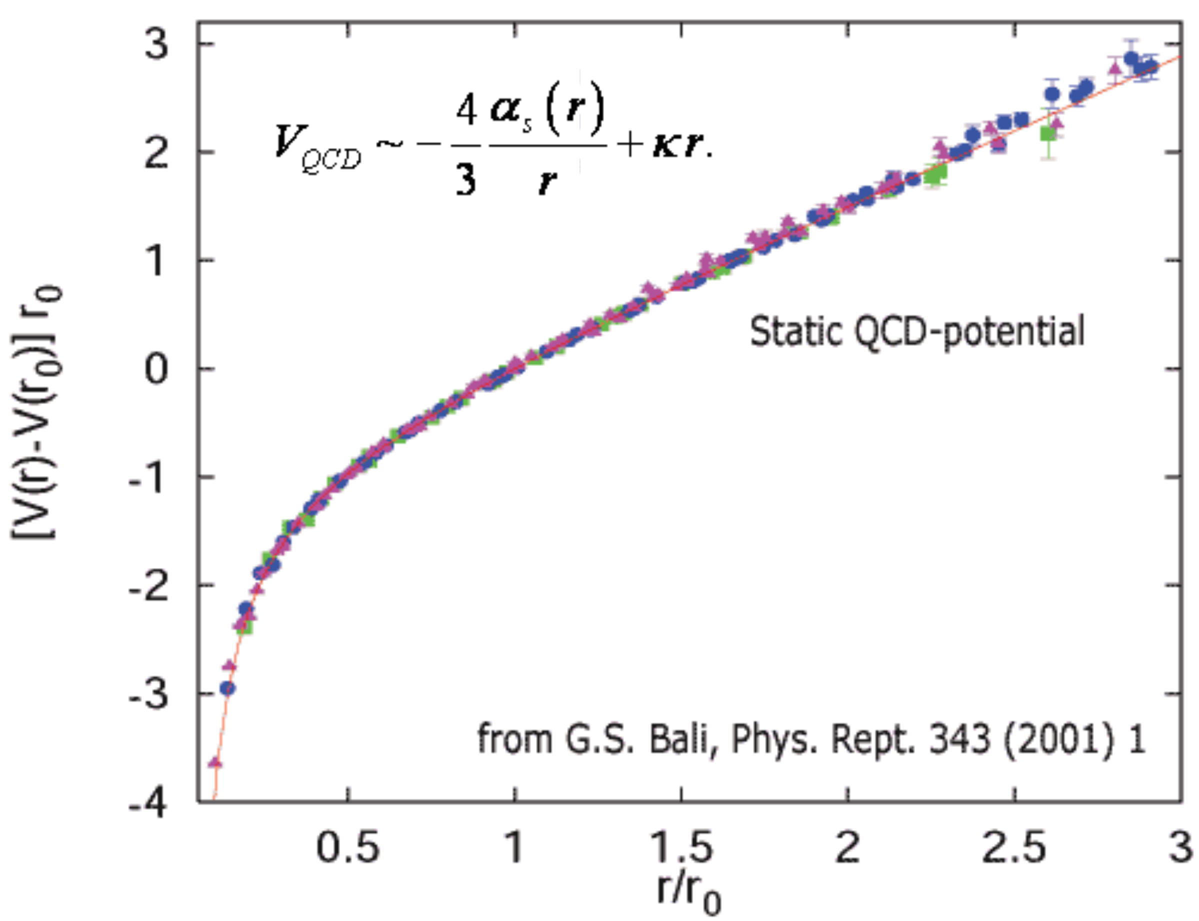
Running QCD coupling

$$\alpha_S(Q) \simeq \frac{2\pi}{b_0 \ln(Q/\Lambda_{QCD})}, \qquad b_0 = 11 - \frac{2}{3}N_F$$

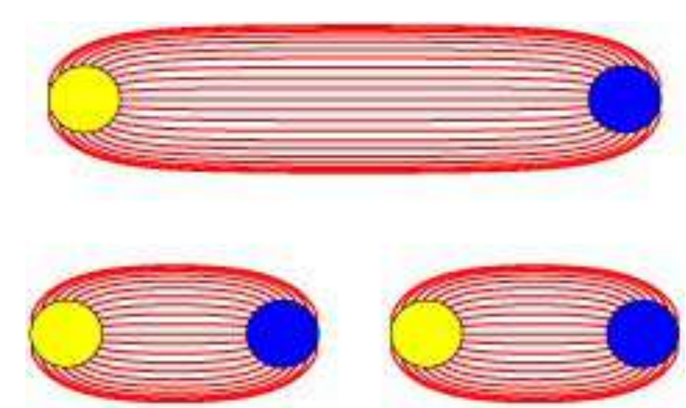
Color charge anti-screening







Short range strong interactions



Color confinement!

Motivation for composite DM

- DM stability: violation of the global flavour symmetries of the composite EFT is extremely suppressed in analogy to the baryon number in the SM

- Naturalness: like in QCD, emergence of the confinement scale through dimensional transmutation is technically natural

- DM neutrality: confinement can lead to SM-neutral dark hadrons

- Suppressed interactions: EFT operators are naturally suppressed by the confinement scale in IR, in addition to a strong suppression by a heavy 'portal' mediating the dark gauge and visible SM sectors in the UV

- Self-interactions: similarly to QCD hadrons, and with proper arrangements of the scales may provide a natural explanation for galactic-structure anomalies

- New observables: with plethora for new opportunities for measurements: new channels for direct/indirect detection, inelastic scattering to excited states, dark absorption, new effects on CMB and $N_{\rm eff}$, new opportunities for collider searches

Types of composite DM

- **Pion-like** $m_q \ll \Lambda$
  - $\Rightarrow$ Flavour G-parity — Y. Bai and R. J. Hill, Phys. Rev. D82, 111701 (2010)
  - $\Rightarrow$ Baryon-like pions — M. R. Buckley and E. T. Neil, Phys. Rev. D87, 043510 (2013)
  - $\Rightarrow$ SIMP with WZW action and dark photon portal — Hochberg at al, PRL 115, 021301 (2015)
- **Meson-like** $m_q > \Lambda$
  - $\Rightarrow$ Composite inelastic DM — Alves et al, Phys. Lett. B692, 323 (2010)
  - $\Rightarrow$ Quirky DM — Kribs et al, Phys. Rev. D81, 095001 (2010)
- **Baryon-like**
  - $\Rightarrow$ Technibaryon DM — Nussinov, Phys. Lett. B165, 55 (1985); Appelquist et al. , Phys. Rev. D88, 014502 (2013); Pasechnik et al, Int. J. Mod. Phys. A 31 (2016) 08, 1650036; Eur. Phys. J. C 74 (2014) 2728
  - $\Rightarrow$ Stealth DM — T. Appelquist et al., Phys. Rev. D92, 075030 (2015)
- **Dark glueballs**
  - $\Rightarrow$ Vector glueballs — J. E. Juknevich, JHEP 08 (2010) 121; Biondini et al, Phys. Lett. B 857 (2024) 138995
  - $\Rightarrow$ Scalar glueballs — A. E. Faraggi, M. Pospelov, Astropart. Phys. 16 (2002) 451; Carenza, Pasechnik, Salinas, Wang, PRL 129 (2022) 26; PRL 135 (2025) 2

Hidden confining Yang-Mills sectors

Let us push the fermion mass scale way above the confinement scale: dark pure SU(N)!

Many works on confining dark $SU(N)$

- **Self-interacting DM**
  E. D. Carlson *et al.*, Astrophys. J. **398** (1992), 43-52
- **Glueball phenomenology**
  A. Soni and Y. Zhang, Phys. Rev. D **93** (2016) no.11, 115025
- **The dark glueball problem**
  J. Halverson *et al.*, Phys. Rev. D **95** (2017) no.4, 043527
- **The nightmare scenario**
  R. Garani *et al.*, JHEP **12** (2021), 139
- **Thermal Squeezeout**
  P. Asadi *et al.*, Phys. Rev. D **104** (2021) no.9, 095013
- **Gravitational waves from confinement**
  W. C. Huang *et al.*, Phys. Rev. D **104** (2021) no.3, 035005

Open questions:

$\Rightarrow$ Do we need to describe the cosmological evolution of the dark gluon gas?

$\Rightarrow$ How do glueball form from dark gluons?

$\Rightarrow$ Is there any constraint on glueball self-interactions?

$\Rightarrow$ Is there a reliable estimate of the glueball relic density?

Strongly coupled sectors at finite temperatures

- **Pure gluons**

  ⇒ Polyakov loop model — Kang, Zhu, Matsuzaki, JHEP 09 (2021) 060; Huang, Reichert, Sannino, Wang, PRD 104 (2021) 035005

  ⇒ Matrix model — Halverson, Long, Maiti, Nelson, Salinas, JHEP 05 (2021) 154

  ⇒ Holographic QCD model — Ares, Henriksson, Hindmarsh, Hoyos, Jokela, PRD 105 (2022) 066020; PRL 128 (2022) 131101

- **Gluons + fermions**

  ⇒ Polyakov loop improved Nambu-Jona-Lasinio model

  Reichert, Sannino, Wang, Zhang, JHEP 01 (2022) 003; Helmboldt, Kubo, Woude, PRD 100 (2019) 055025

  ⇒ Linear sigma model — Helmboldt, Kubo, Woude, PRD 100 (2019) 055025

  ⇒ Polyakov Quark Meson model — RP, Reichert, Sannino, Wang, JHEP 02 (2024) 159

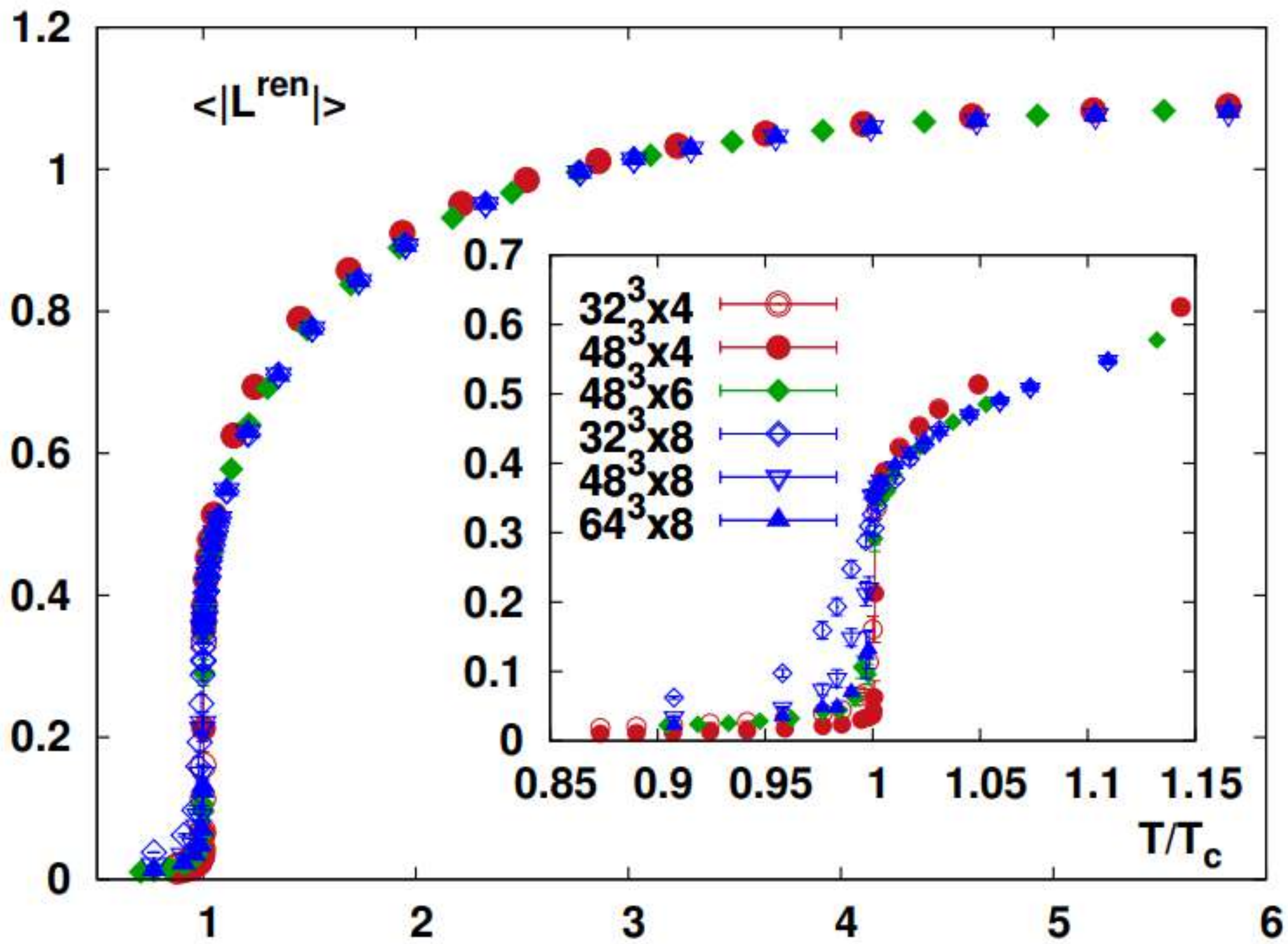
Confining Yang-Mills theories are well studied by lattice simulations, and the robust results are available

Polyakov Loop Model

R. D. Pisarski, Phys. Rev. D 62 (2000), 111501

$$\ell(x) = \frac{1}{N}\mathrm{Tr}[\mathsf{L}] \equiv \frac{1}{N}\mathrm{Tr}\left[\mathcal{P}\exp\left[i\,g\int_0^{1/T} A_0(\tau,x)d\tau\right]\right]$$

P. M. Lo et al., Phys. Rev. D 88 (2013), 074502

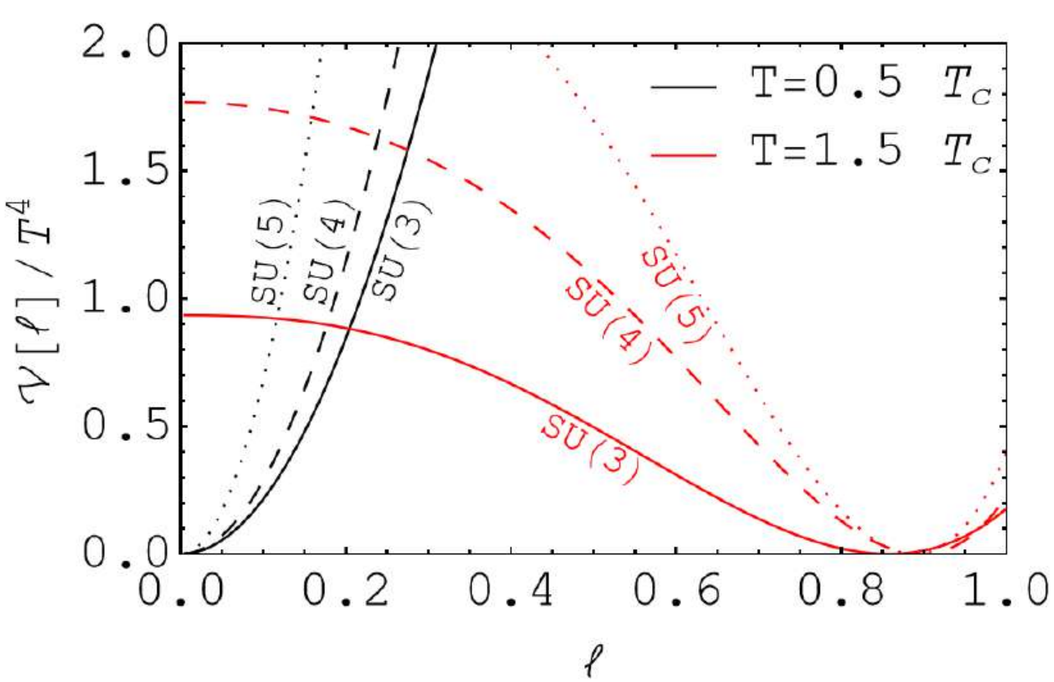


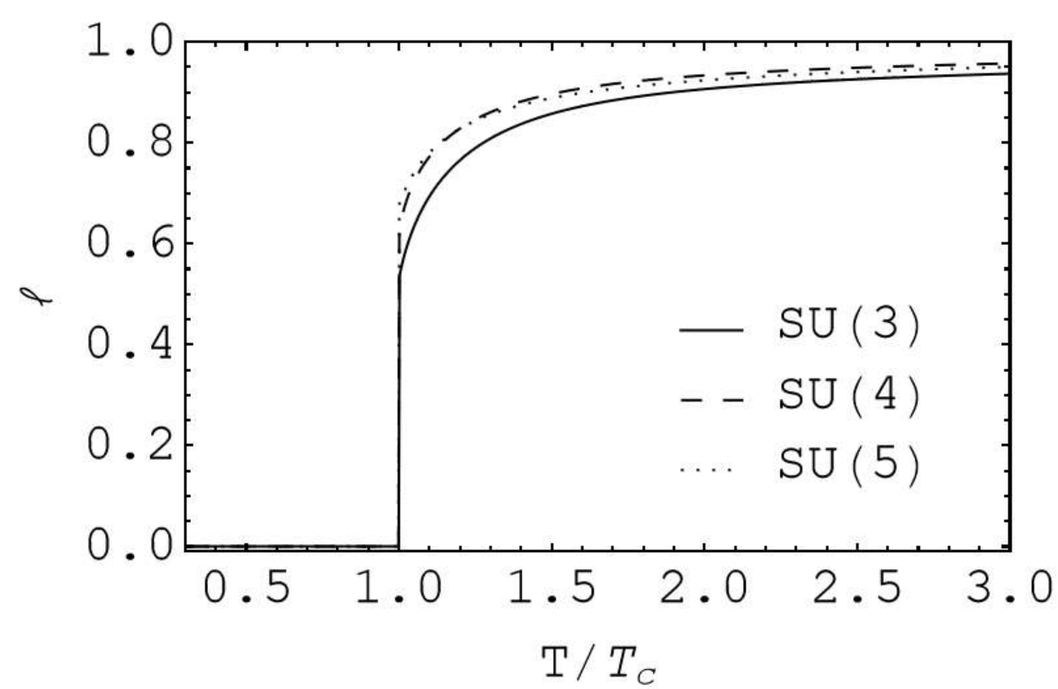
PLM potential

The behaviour of ℓ is described as a field in an effective potential

$$\mathcal{V}[\ell] = T^4\left(-\frac{b_2(T)}{2}|\ell|^2 + b_4|\ell|^4 - b_3\left(\ell^N + \ell^{*N}\right) + b_6|\ell|^6 + b_8|\ell|^8 \right)$$

determined by symmetry arguments



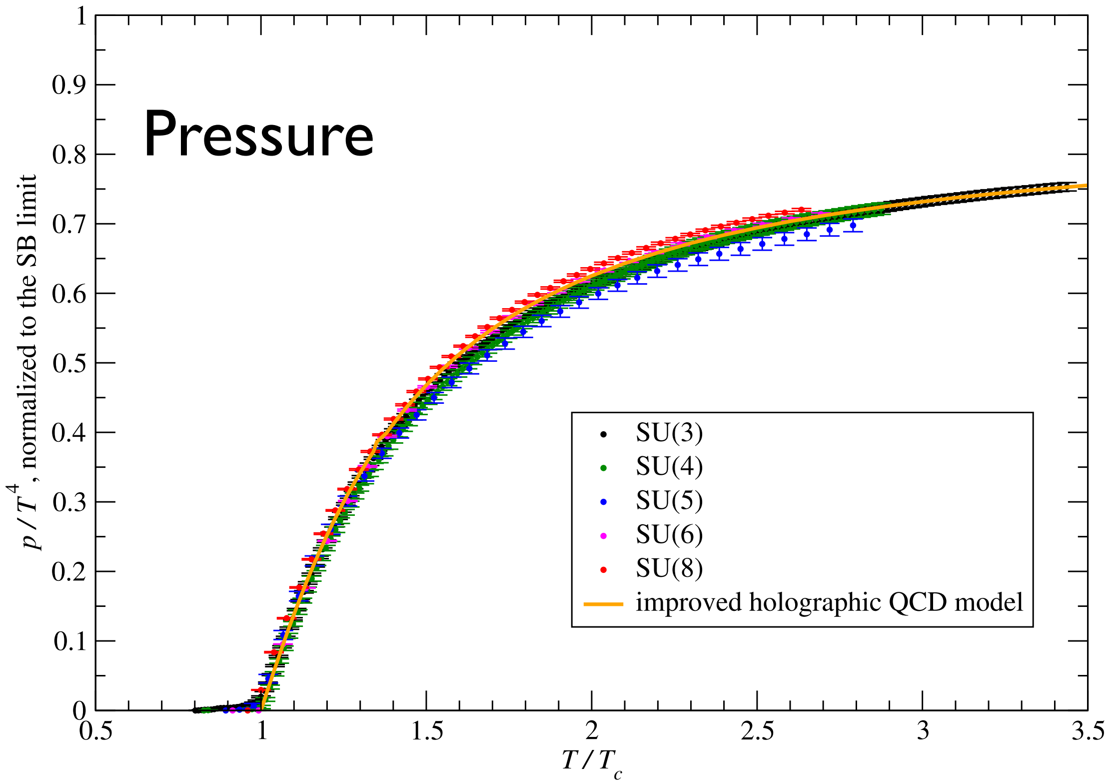


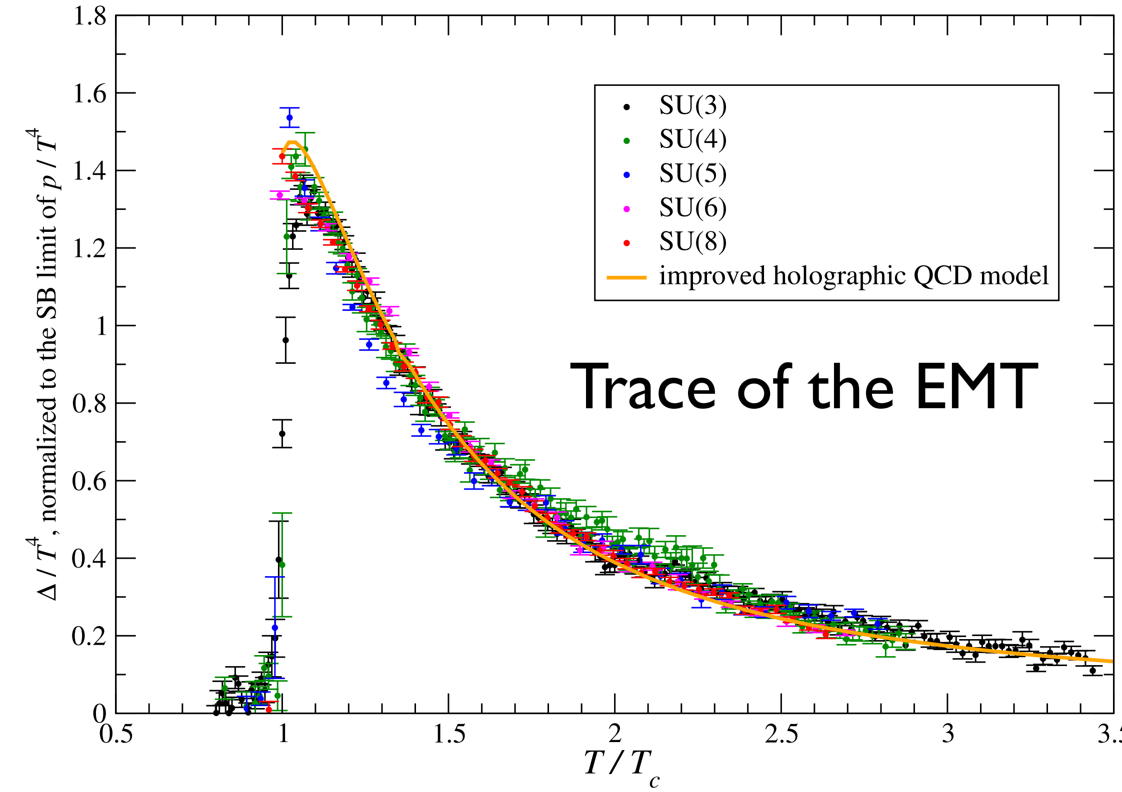
Carenza, RP, Salinas, Wang, PRL 129, 26 (2022) 26
Carenza, Ferreira, RP and Wang, PRD 108, 12 (2023)

Fitting the PLM potential to the lattice data

Lattice data

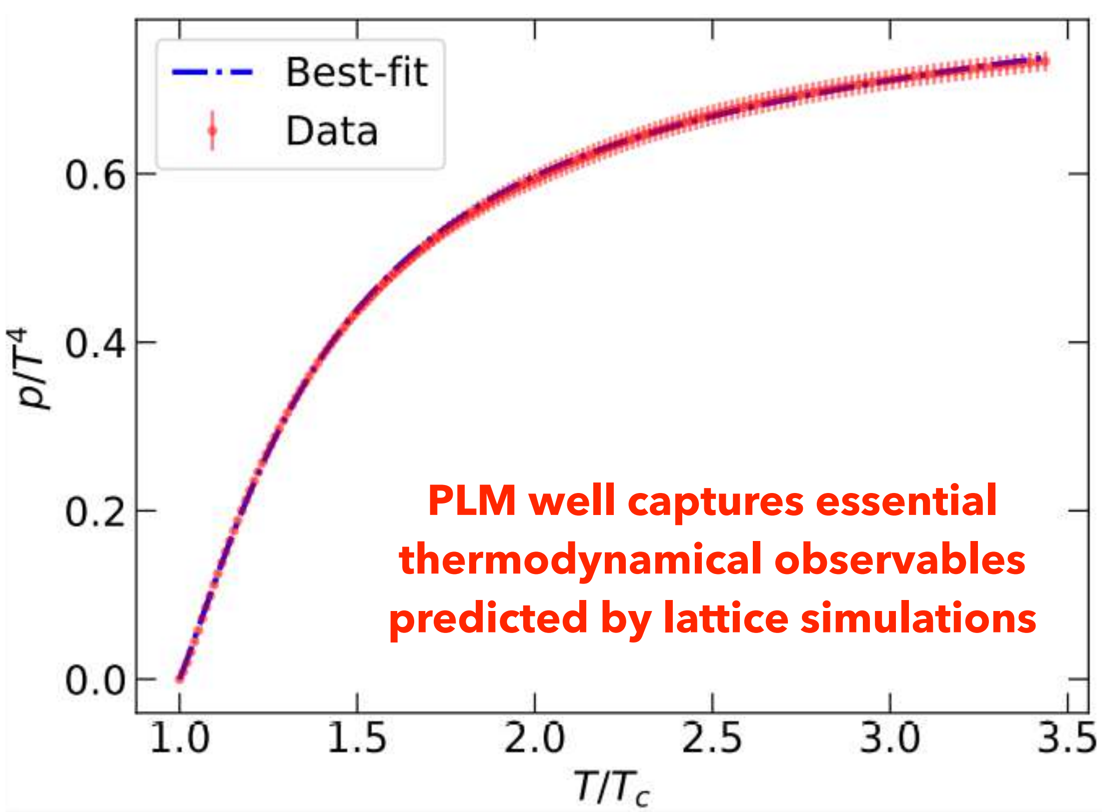
Marco Panero, Phys.Rev.Lett. 103 (2009) 232001

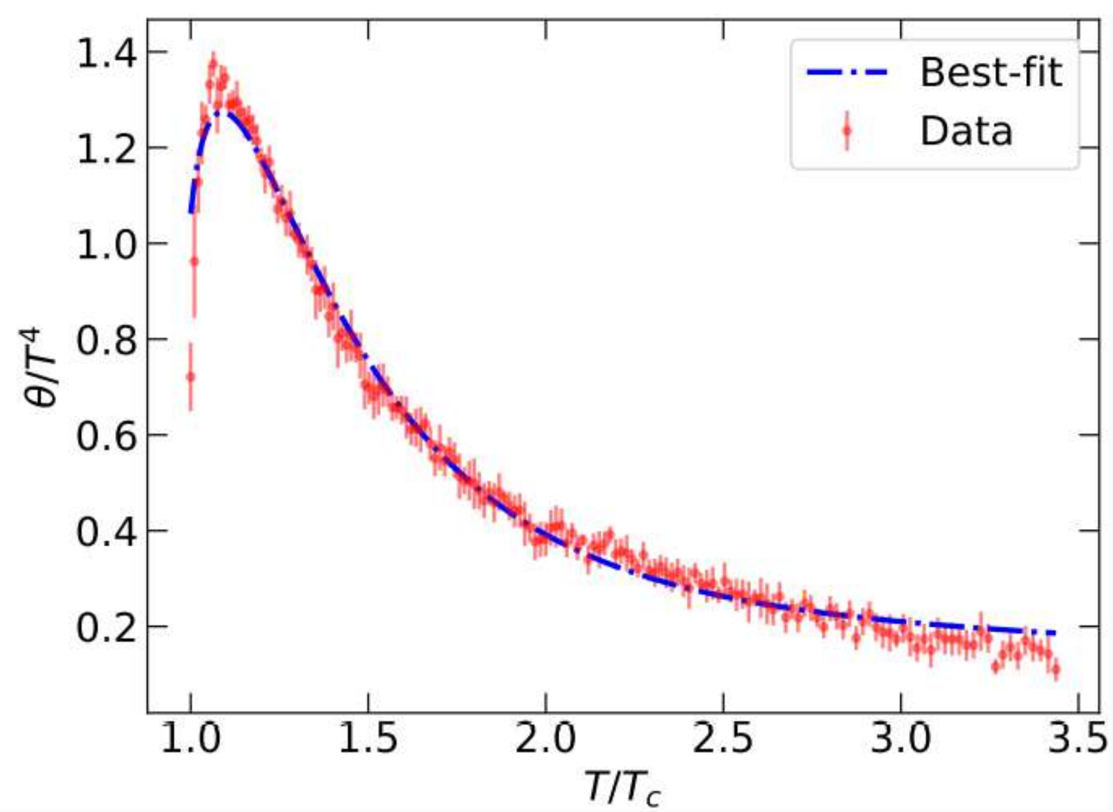




Best fit of the PLM potential

Huang, Reichert, Sannino and Wang, PRD 104 (2021) 035005

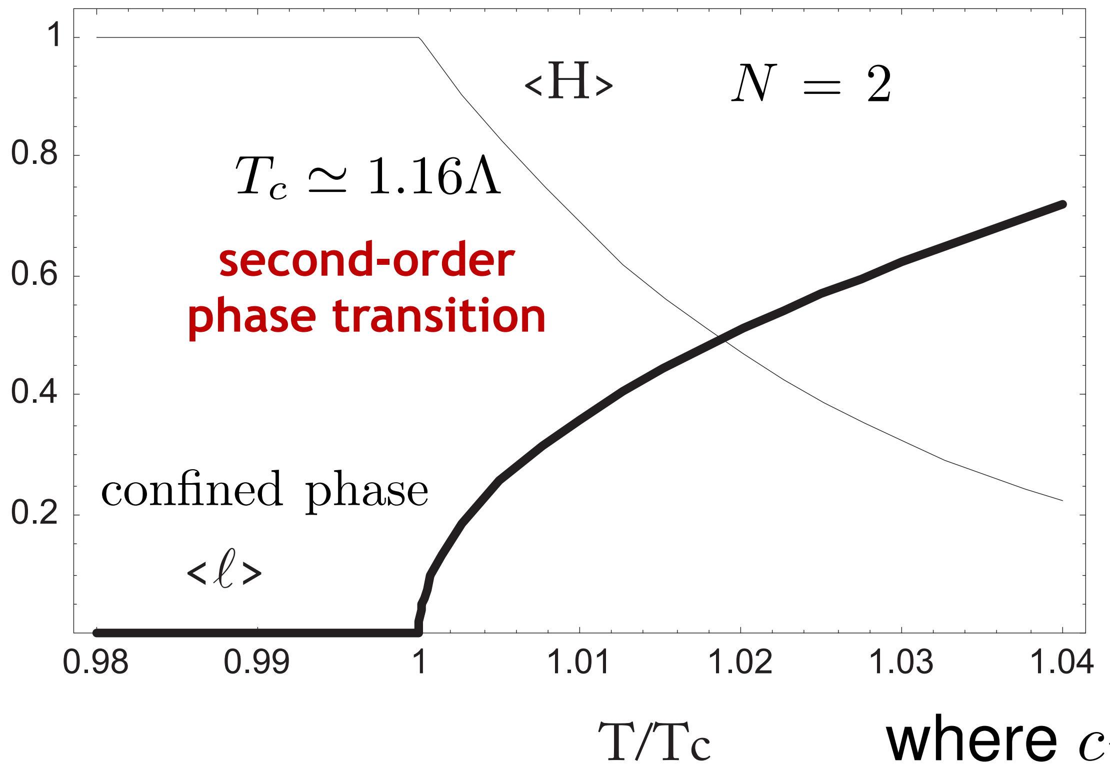




Dark gluon-glueball dynamics

Carenza, RP, Salinas, Wang, PRL129 (2022) no.26, 26

- In the literature, for glueball dark matter production, only ϕ^5 interaction is considered, making the $3 \to 2$ annihilation the only relevant process for DM formation
- However, since glueball is strongly coupled, this naive calculation is not rigorous. A non-perturbative method is required.
- The dark gluon-glueball dynamics can be effectively described by considering the dimension-4 glueball field $\mathcal{H} \propto \mathrm{tr}(G^{\mu\nu}G_{\mu\nu})$:



$$\mathcal{L} = \frac{c}{2}\frac{\partial_\mu \mathcal{H} \partial^\mu \mathcal{H}}{\mathcal{H}^{3/2}} - V[\mathcal{H}, \ell] \qquad c = \frac{1}{2\sqrt{e}}\left(\frac{\Lambda}{m_{\rm gb}}\right)^2$$

$$V[\mathcal{H}, \ell] = \frac{\mathcal{H}}{2}\ln\left[\frac{\mathcal{H}}{\Lambda^4}\right] + T^4\mathcal{V}[\ell] + \mathcal{H}\mathcal{P}[\ell] + V_T[\mathcal{H}]$$

We keep the lowest order in $\mathcal{P}[\ell]$ $\qquad \mathcal{P}[\ell] = c_1|\ell|^2$

where c_1 is determined by the lattice results (jumping of gluon condensate).

F. Sannino, *Polyakov loops versus hadronic states*, *Phys. Rev. D* **66** (2002) 034013 [hep-ph/0204174].

Thermal evolution of the glueball-dark gluon system

Carenza, RP, Salinas, Wang, PRL 129, 26 (2022)

- **The glueball field evolves evolves according to the EFT:**

$\mathcal{H} \propto \text{tr}(G^{\mu\nu}G_{\mu\nu}) = 2^{-8}c^{-2}\phi^4 \qquad c = \frac{1}{2\sqrt{e}}\left(\frac{\Lambda}{m_{\text{gb}}}\right)^2$

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V[\phi,\ell]\,,$$

$$V[\phi,\ell] = \frac{\phi^4}{2^8c^2}\left[2\ln\left(\frac{\phi}{\Lambda}\right) - 4\ln 2 - \ln c\right] + \frac{\phi^4}{2^8c^2}\mathcal{P}[\ell] + T^4\mathcal{V}[\ell]\;,$$

$$\mathcal{P}[\ell] = c_1|\ell|^2\,,$$

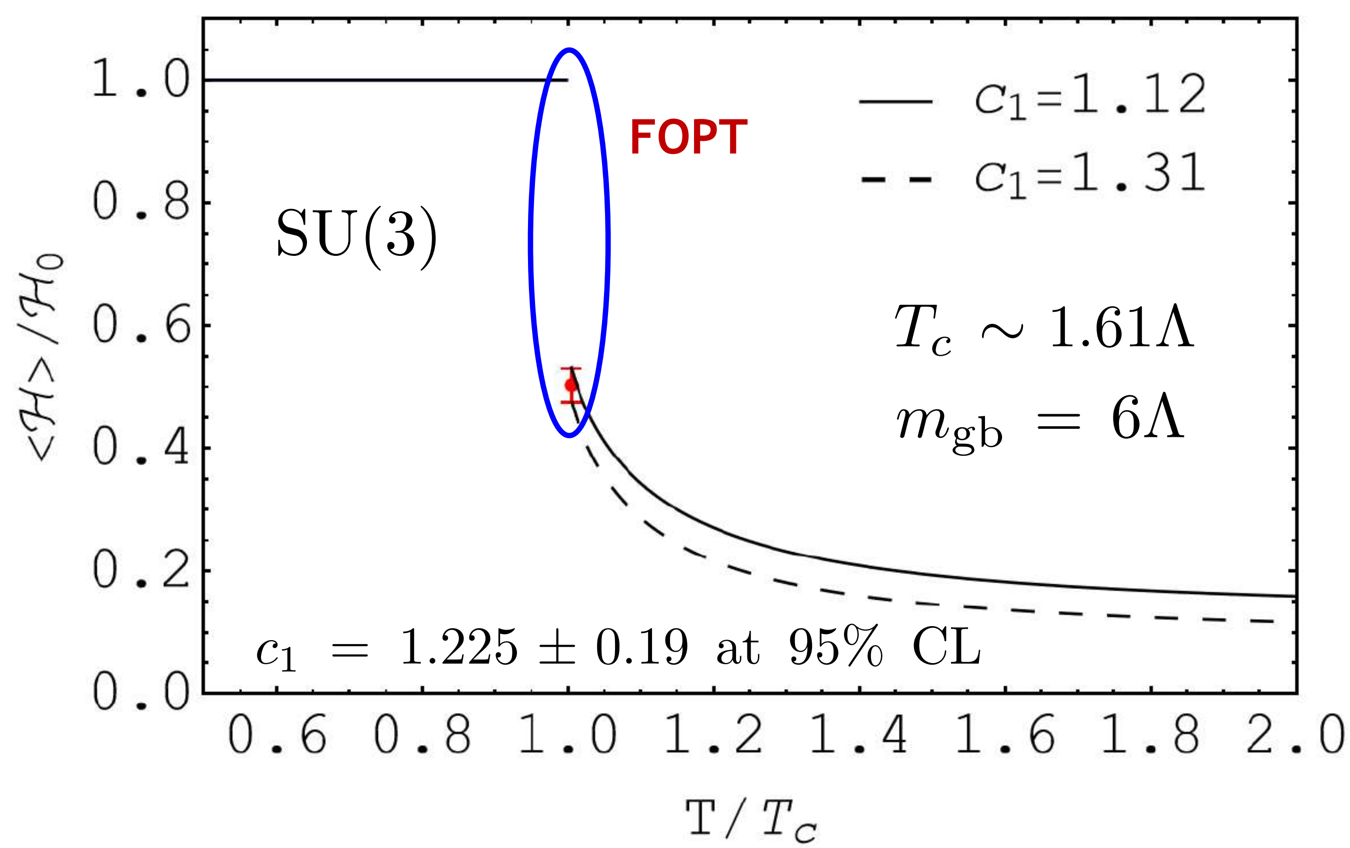
$$\mathcal{V}[\ell] = -\frac{b_2(T)}{2}|\ell|^2 + b_4|\ell|^4 - b_3(\ell^3 + (\ell^*)^3)\,,$$

$$b_2(T) = \sum_{i=0}^{4} a_i\left(\frac{T_c}{T}\right)^i\,,$$

- **Fits to lattice results**

a_0	a_1	a_2	a_3	a_4	b_3	b_4
3.72	−5.73	8.49	−9.29	0.27	2.40	4.53

Huang, Reichert, Sannino and Wang, PRD 104 (2021) 035005



- **Integrating out the Polyakov loop in the high-T phase provides**

$$V[\phi,T] = V[\phi,\ell(\phi,T)]$$

matching the size of discontinuity to lattice data

F. Sannino, *Polyakov loops versus hadronic states*, *Phys. Rev. D* **66** (2002) 034013 [hep-ph/0204174].

Cosmological evolution equation

- The glueball field is considered homogeneous and evolves in expanding FLRW universe, with the E.O.M.

$$\ddot{\phi} + 3H\dot{\phi} + \partial_\phi V[\phi, T] = 0\,,$$

- The time variable is found in terms of the photon temperature:

$$t = \frac{1}{2}\sqrt{\frac{45}{4\pi^3 g_{*,\rho}(T_\gamma)}\frac{m_P}{T_\gamma^2}}\,, \qquad T_\gamma = \xi_T T$$

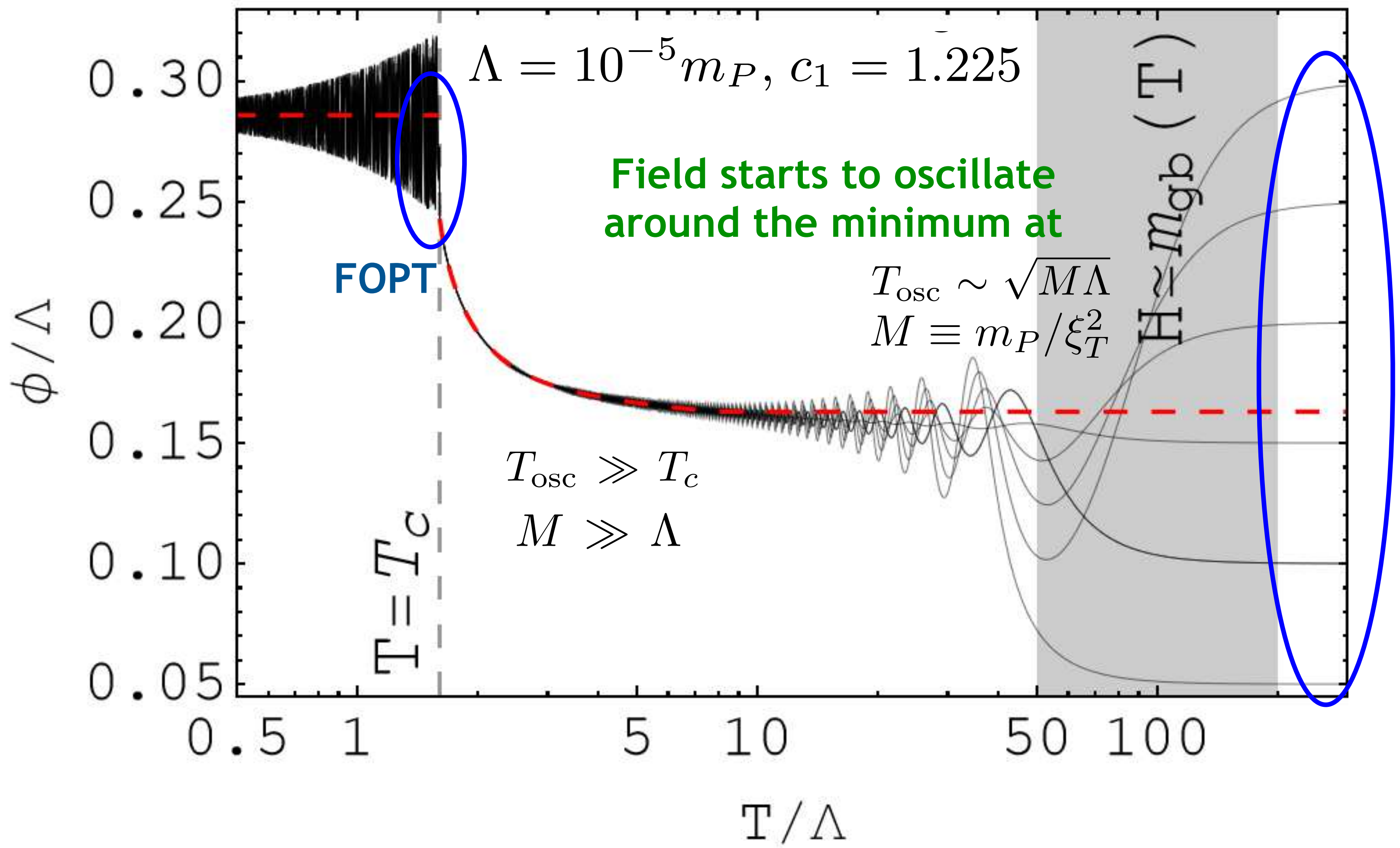
where ξ_T denotes the visible-to-dark sector temperature ratio and $m_P = 1.22 \times 10^{19}$ GeV is the Planck mass and $g_{*,\rho}$ is the number of energy-related degrees of freedom.

- E.O.M. in terms of the dark sector temperature:

$$\frac{4\pi^3 g_{*,\rho}}{45 m_P^2}\xi_T^4 T^6 \frac{d^2\phi}{dT^2} + \frac{2\pi^3}{45 m_P^2}\frac{dg_{*,\rho}}{dT}\xi_T^4 T^6 \frac{d\phi}{dT} + \partial_\phi V[\phi, T] = 0$$

encodes non-perturbative dynamics of the glueball field at finite T

Cosmological evolution



In the deconfined regime, the field evolution is dominated by Hubble friction (slow evolution)

Oscillations have long time to decay regardless of the initial condition

non-linear interaction terms are important for large amplitudes

- Field starts to oscillate around the minimum of the potential when $H \simeq m_{\rm gb}$ with temperature $T_{\rm OSC} \sim \sqrt{M\Lambda}$
- In early times in deconfined regime, for different initial conditions the field evolution follows the minimum (red dashed line).
- First order phase transition washes out any dependence on initial conditions.

Relic abundance

- Energy stored in these oscillations around $\phi_{\rm min} \approx 0.28\Lambda$ is the relic DM abundance, $\Omega h^2 = \rho/\rho_c$ (critical density $\rho_c = 1.05 \times 10^4\,{\rm eV\,cm^{-3}}$)

$$\rho = \frac{2\pi^3}{45} g_{*,\rho}(T) \frac{T^6}{M^2} \left(\frac{d\phi}{dT}\right)^2 + V[\phi]$$

- Then the relic density today is calculated:

$$\Omega h^2 = \frac{\Lambda}{\rho_c/h^2} \left\langle \frac{\tilde{\rho}}{\tilde{T}^3} \right\rangle_f T_f^3 \left(\frac{T_{\gamma,0}}{\zeta_T T_f}\right)^3 = 0.12 \zeta_T^{-3} \frac{\Lambda}{\Lambda_0}\,,$$

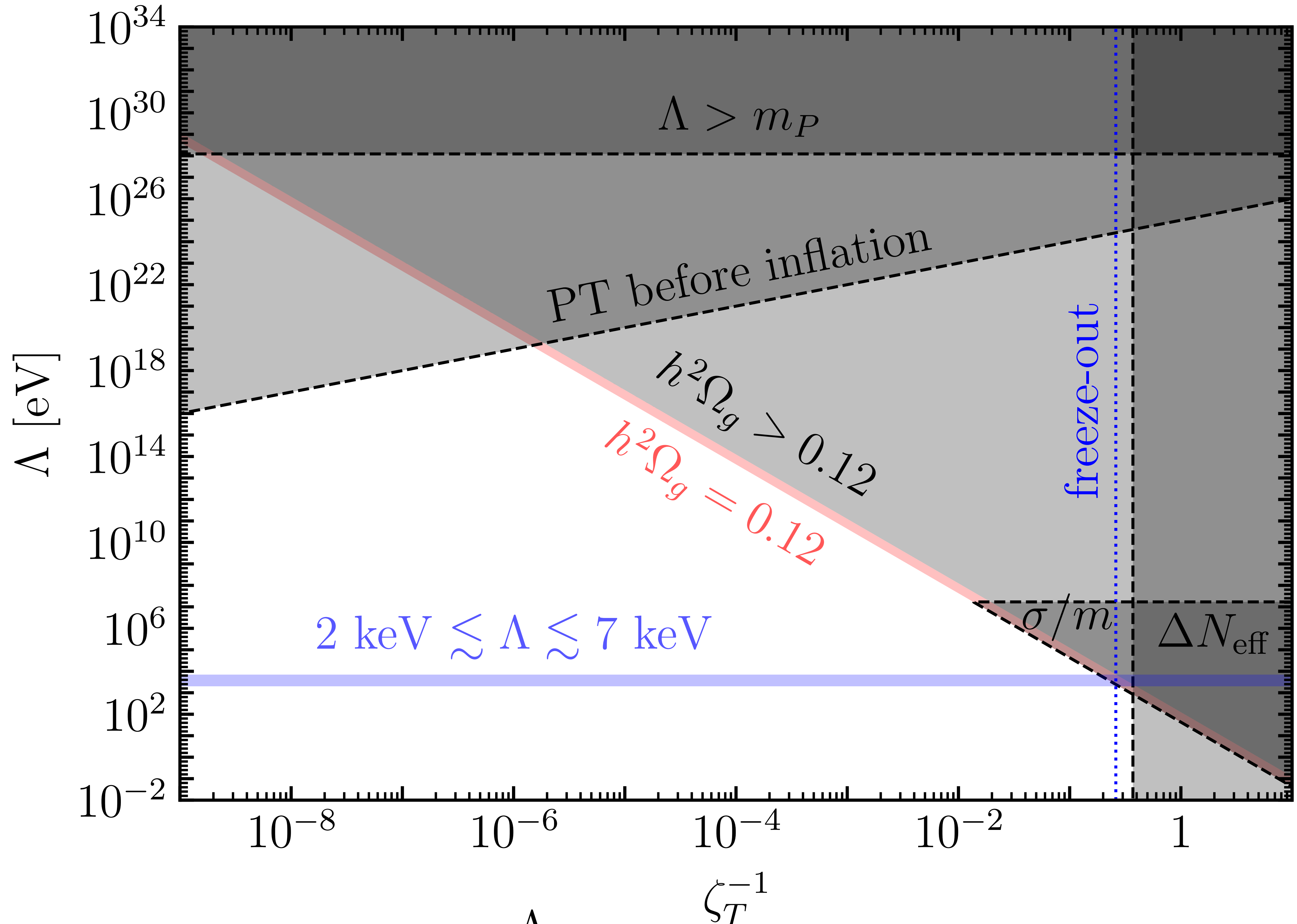
with dilution factor $(T_{\gamma,0}/\zeta_T T_f)^3$ to consider the Universe expansion

- Below freeze-out temperature, the predicted glueball relic density is

$$0.12\zeta_T^{-3} \frac{\Lambda}{137.9\,{\rm eV}} \lesssim \Omega h^2 \lesssim 0.12\zeta_T^{-3} \frac{\Lambda}{82.7\,{\rm eV}}, \quad 1.035 < c_1 < 1.415$$

Glueball DM parameter space; no portal yet!

Carenza, RP, Salinas, Wang, PRL 129 (2022) no.26, 26



$$\Omega_{\rm DM} h^2 \simeq 0.12\, \zeta_T^{-3} \frac{\Lambda}{\Lambda_0}$$

$$100\ \text{eV} \lesssim \Lambda_0 \lesssim 400\ \text{eV}$$

Glueball Axion Like Particles (ALPs)

Fundamental gauge theory ⟷ Glueball EFT

$$\mathcal{L}_{\rm SU(N)} = -\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu a} + \frac{\theta}{4}G^a_{\mu\nu}\tilde{G}^{\mu\nu a}\,, \qquad \mathcal{L}_{\rm eff} = \frac{1}{2}\partial_\mu\mathcal{H}\partial^\mu\mathcal{H} + \frac{1}{2}\partial_\mu\mathcal{A}\partial^\mu\mathcal{A} - V_{\rm eff}(\mathcal{H},\mathcal{A})$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc}A^b_\mu A^c_\nu \qquad \mathcal{H} \equiv 0^{++} \qquad \mathcal{A} \equiv 0^{-+}$$

Relevant composite operators

$$\mathcal{H}^4 \equiv -\frac{\beta(g)}{2g}G^a_{\mu\nu}G^{\mu\nu a}\,, \qquad \mathcal{A}\,\mathcal{H}^3 \equiv G^a_{\mu\nu}\tilde{G}^{\mu\nu a}$$

⇓ Trace anomaly ⇓

$$\partial_\mu D^\mu = \frac{\beta(g)}{2g}G^a_{\mu\nu}G^{\mu\nu a} = -\mathcal{H}^4 \qquad \partial_\mu D^\mu = -\Theta^\mu_\mu = 4V_{\rm eff} - \frac{\partial V_{\rm eff}}{\partial\mathcal{H}}\mathcal{H} - \frac{\partial V_{\rm eff}}{\partial\mathcal{A}}\mathcal{A}$$

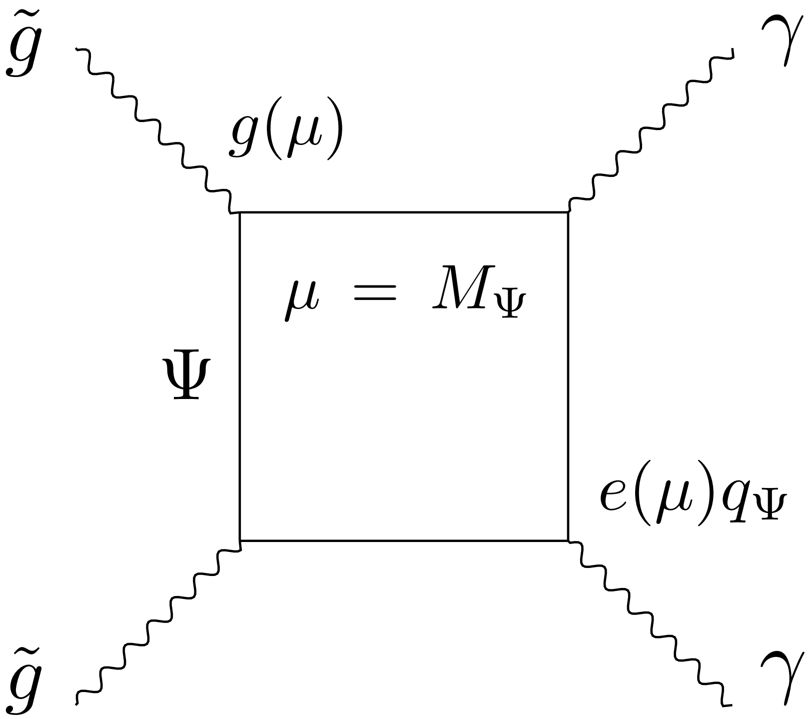
⇓ ⇓

$$V_{\rm eff} \simeq c_0\mathcal{H}^4\ln\left(\frac{\mathcal{H}}{\Lambda}\right) + \frac{\theta}{4}\mathcal{A}\,\mathcal{H}^3 + \mathcal{H}^4 f\left(\frac{\mathcal{A}}{\mathcal{H}}\right) + c_1\mathcal{H}^4 + c_2\mathcal{H}^2\mathcal{A}^2 + c_3\mathcal{A}^4 + c_4\mathcal{H}\,\mathcal{A}^3$$

Glueball potential

Carenza, RP and Wang, PRL135 (2025) 2, 021001

Direct fermion portal to the dark gauge sector



✓ Introduce a heavy Dirac fermion (dark quark): dark SU(N)-charged and electrically charged

✓ Relevant dim-8 operators below the cutoff scale but above the confinement scale $\Lambda \ll M_\Psi$:

$$\mathcal{L}_{\rm eff} \supset \frac{\tau^2 \alpha^2}{M_\Psi^4} \left[c_\gamma \, G^a_{\mu\nu} G^{\mu\nu a} F_{\alpha\beta} F^{\alpha\beta} + \tilde{c}_\gamma \, G^a_{\mu\nu} \tilde{G}^{\mu\nu a} F_{\alpha\beta} \tilde{F}^{\alpha\beta} \right]$$

✓ Dirac fermion annihilation into the SM bath strongly dominate due to the condition on the annihilation rates at EFT cutoff scale:

$$\epsilon \equiv \frac{\Gamma_{\Psi\bar{\Psi}\to\tilde{g}\tilde{g}}}{\Gamma_{\Psi\bar{\Psi}\to X_{\rm SM}}} \ll 1 \qquad\qquad T \sim M_\Psi$$

leading to a suppression of the dark-to-visible temperatures ratio:

$$\zeta_T^{-1} = \left(\frac{\epsilon}{N^2 - 1} \right)^{1/4} \left[\frac{g_{*,s}(T_\gamma^{(0)})}{g_{*,s}(M_\Psi)} \right]^{1/3} \ll 1 \qquad\qquad \zeta_T^{-3} \Lambda / \Lambda_0 \simeq 1$$

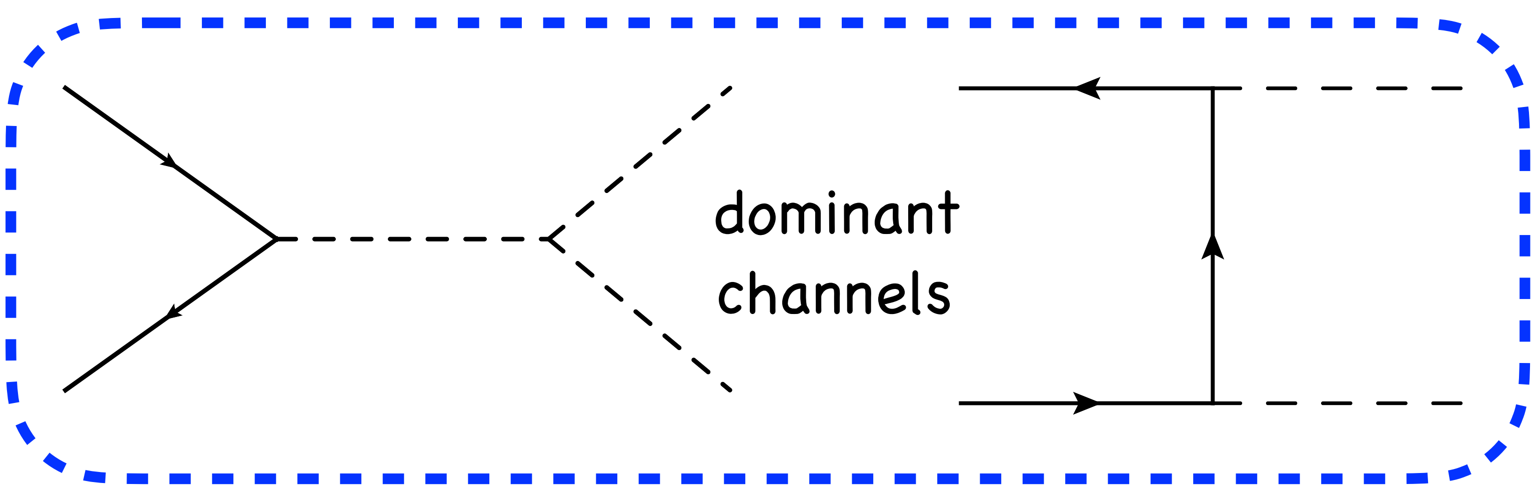
SM bath reheating via fermion annihilation into Higgs

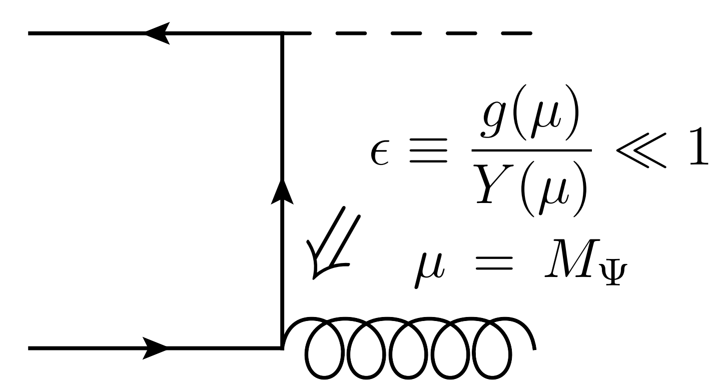
✓ In order to generate a large mass scale of the Dirac fermion, one should consider an additional scalar singlet that could couple to Higgs via potential making Higgs to interact with the fermion

$$\mathcal{L}_{\rm Yuk} = Y \Phi \Psi \bar{\Psi} \qquad Y \langle \Phi \rangle \sim M_\Psi$$

$$V_\Phi = \frac{1}{2}\Phi^2 + \kappa_\Phi \Phi^3 + \lambda_\Phi \Phi^4 + \kappa_{H\Phi} \Phi H H^\dagger + \lambda_{H\Phi} \Phi^2 H H^\dagger$$

✓ The singlet scalar - Higgs mixing enables fermions to annihilate into Higgs final states. Introducing a small ratio between Yukawa and SU(N) gauge couplings at the cutoff scale, one reheats the SM bath relative to the dark gluons at the fermion annihilation





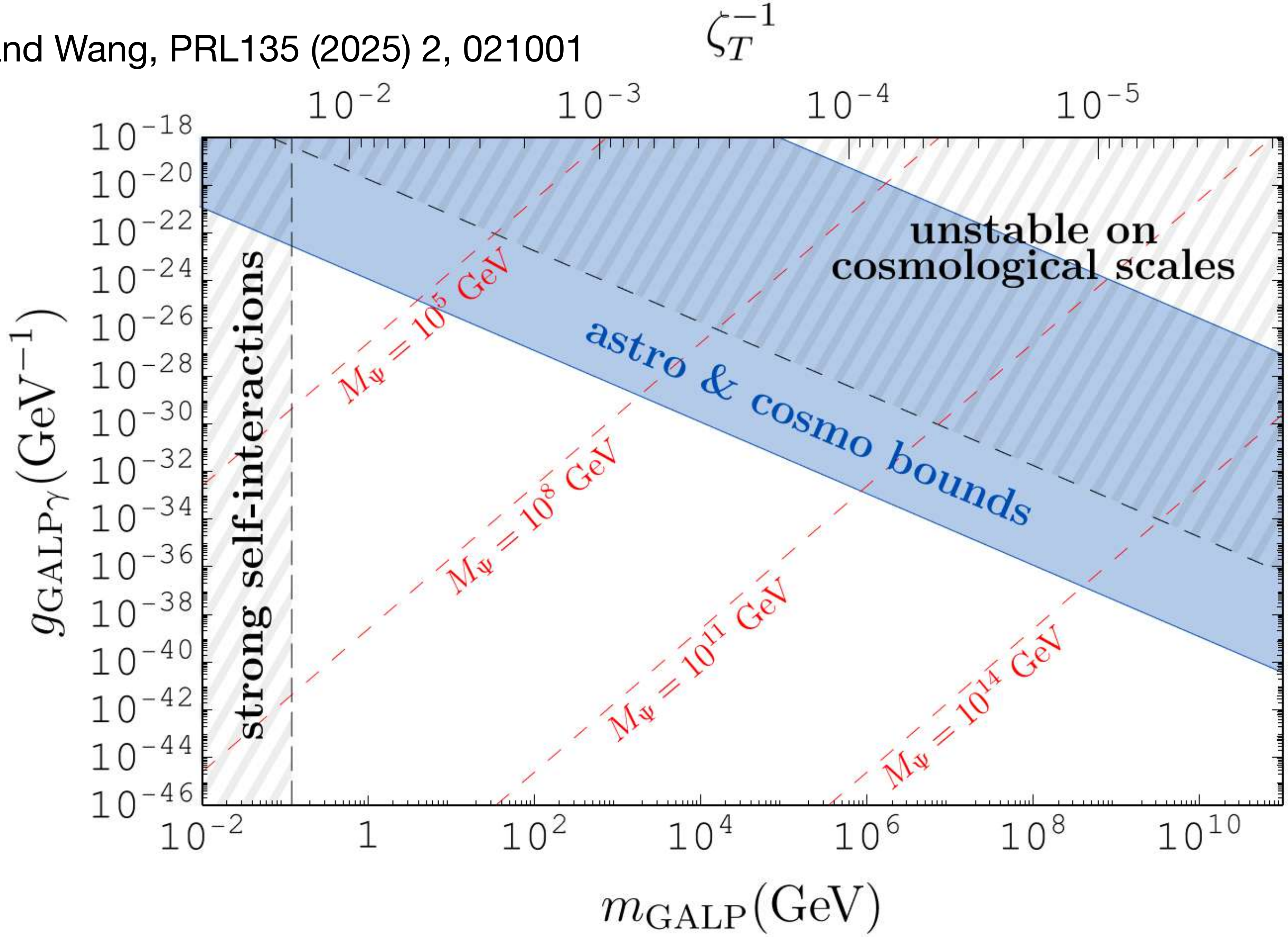
GALP-photon coupling scaling

$$g_{\mathrm{GALP}\gamma} = 2.45 \times 10^{-7}\,\mathrm{GeV}^{-1}\,\kappa \left[\frac{m_{\mathrm{GALP}}}{\mathrm{GeV}}\right]^3 \left[\frac{M_\Psi}{\mathrm{GeV}}\right]^{-4}$$

to be compared to the standard KSVZ axion case:

$$g_{a\gamma} = 2 \times 10^{-10}\,\mathrm{GeV}^{-1}(m_a/\,\mathrm{eV})$$

Carenza, RP and Wang, PRL135 (2025) 2, 021001



GALPs vs ALPs

- Not a composite axion:

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$\Rightarrow$ Glueball in general is not a solution of the strong CP problem

- No hierarchy problem:

$\Rightarrow$ For a standard axion: $\mathcal{L} = -\frac{1}{4} g_{a\gamma} a \, F_{\mu\nu} \tilde{F}^{\mu\nu} \,,$

$\Rightarrow$ $a \to \gamma\gamma$ decay rate: $\Gamma_\gamma = \frac{g_{a\gamma}^2 m_a^3}{64\pi} \simeq 3.3 t_{\rm U}^{-1} \left[\frac{g_{a\gamma}}{10^{-7}\ {\rm GeV}^{-1}} \right]^2 \left(\frac{m_a}{\rm eV} \right)^3 ,$

$\Rightarrow$ Stability on cosmological scale: $g_{a\gamma} \lesssim 5.5 \times 10^{-7}\ {\rm GeV}^{-1} \left(\frac{m_a}{\rm eV} \right)^{-3/2}$

$\Rightarrow$ PQ scale: $f_a \simeq \xi \frac{\alpha}{2\pi g_{a\gamma}} \simeq 10^{17}\ {\rm GeV} \left(\frac{g_{a\gamma}}{10^{-20}\ {\rm GeV}^{-1}} \right)^{-1} ,$

$\Rightarrow$ Largest axion DM mass scale: $f_a \lesssim M_{\rm P}$ $\Rightarrow$ $m_a \lesssim 30\ {\rm GeV}$

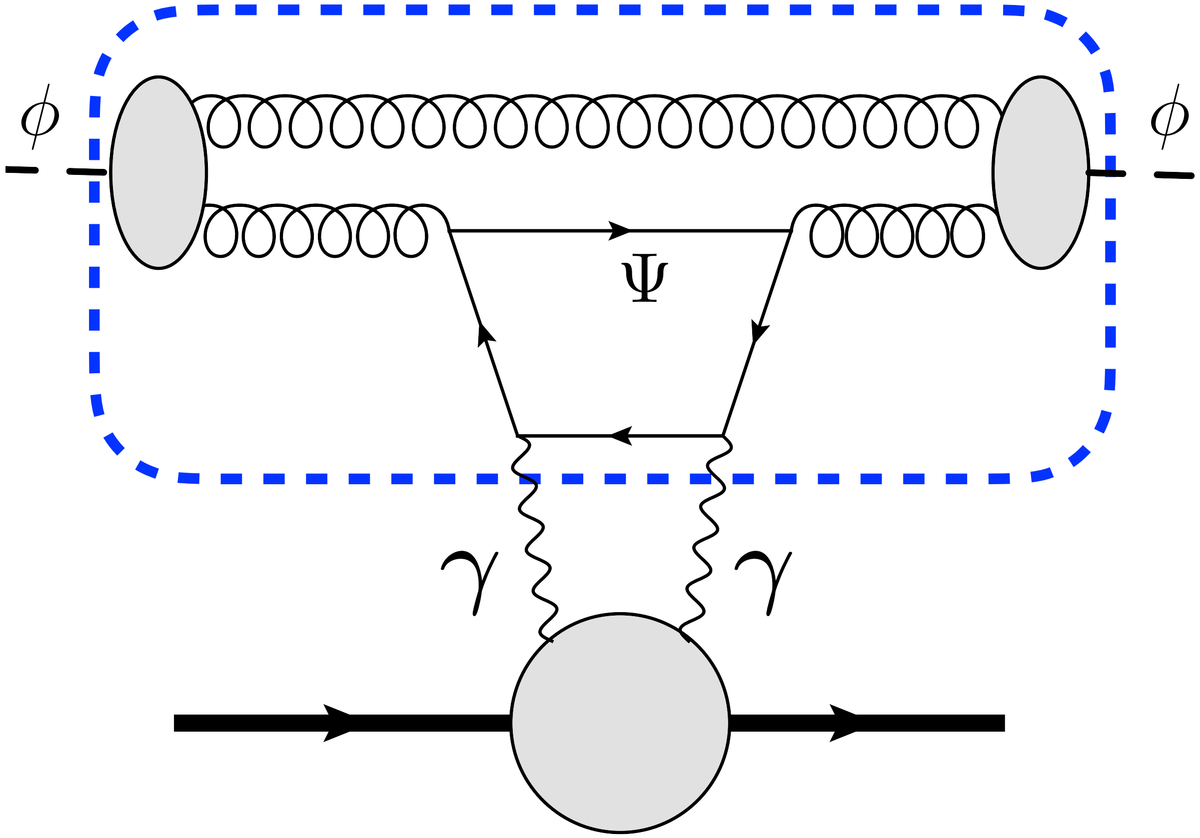
$\Rightarrow$ 'Super-Planckian' PQ scale $f_a \gg M_{\rm P}$ in order to suppress axion decay!

$\Rightarrow$ No issue with GALPs: new parameter space between ALPs and WIMPs!

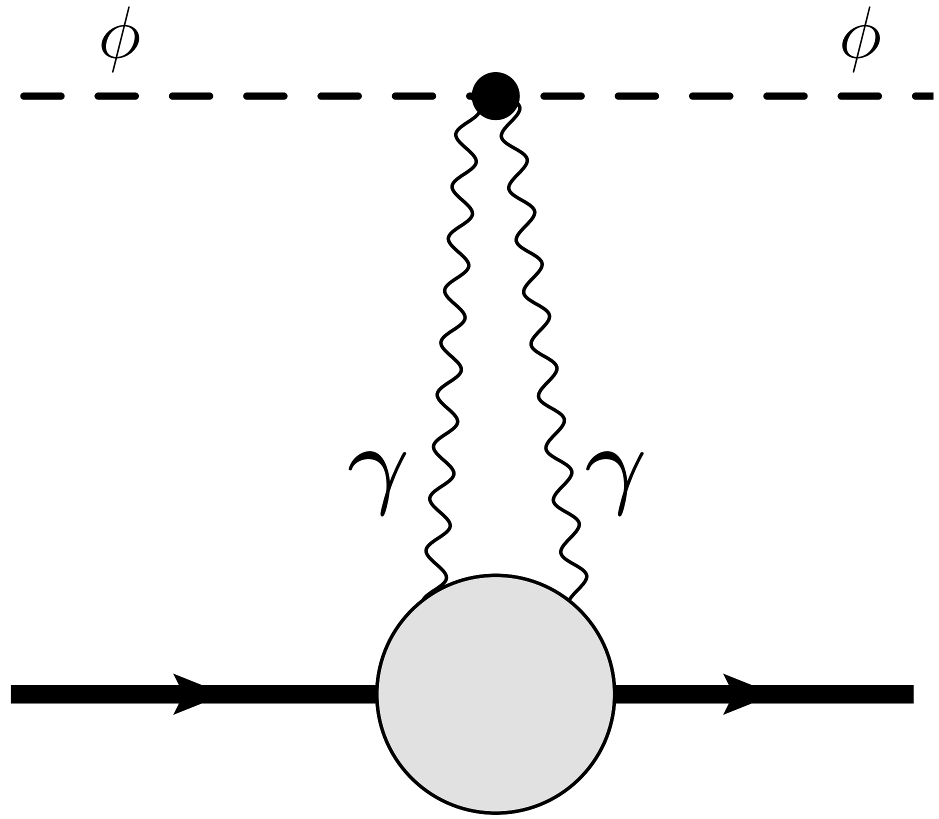
- Rich phenomenology

GALPs Direct Detection prospects: photon mediation

I. Elastic GALP-nucleon scattering with di-photon mediation:

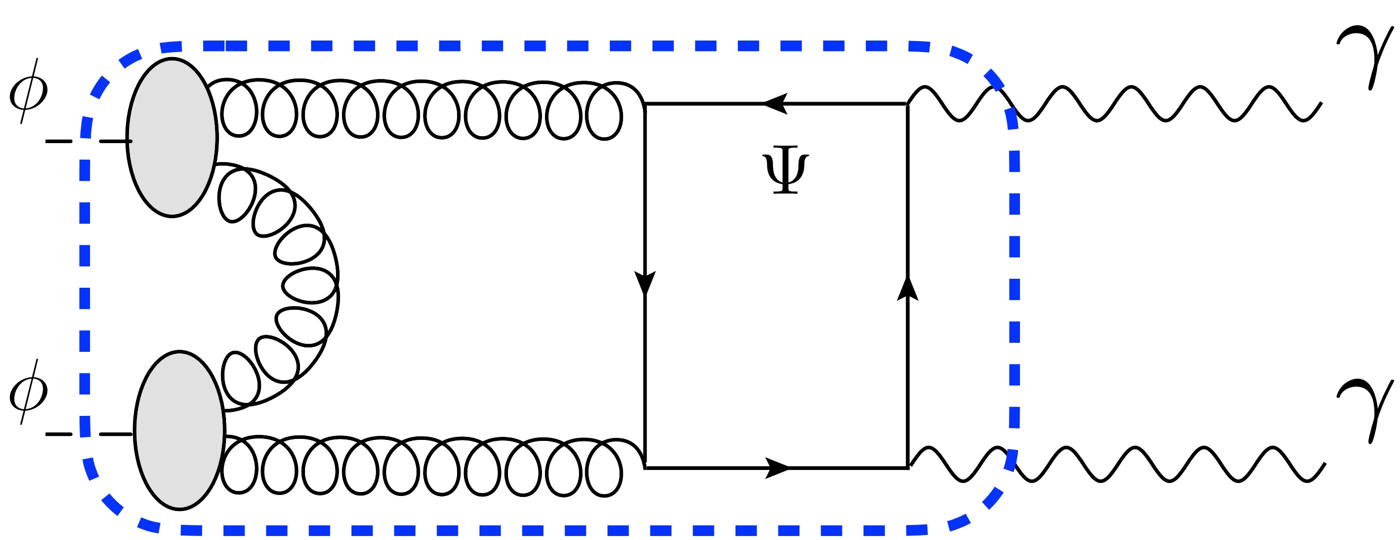


$\Rightarrow$



Enhancement of the photon flux favours large-Z nuclear targets!

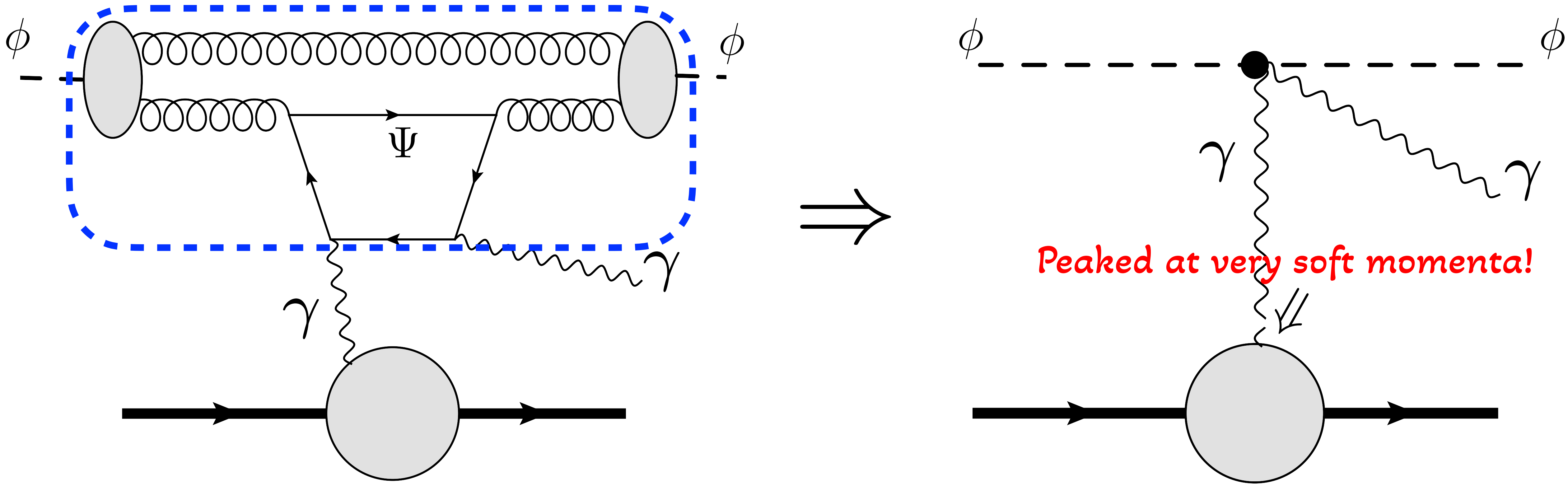
The same operator drives GALP di-photon annihilation in the Galaxy: indirect DM detection signature:



BUT! The box-amplitude is suppressed due to cosmological bounds!

GALPs Direct Detection prospects: photon mediation

II. Quasi-elastic GALP-nucleon scattering with photon mediation and emission:

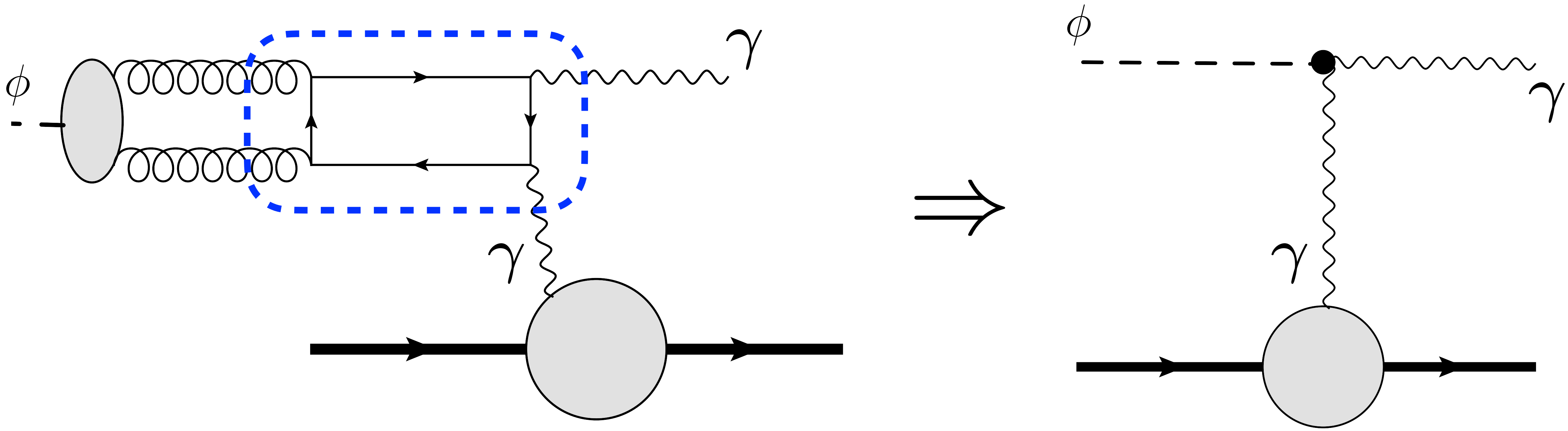


✓ As the photon flux in the nuclear target is peaked at low photon momentum fractions and transverse momenta, the cross section would be dominated to soft "no-recoil" contributions.

✓ A key novel signature would be a GALP-induced real photon emission recoiled against the GALP itself.

GALPs Direct Detection prospects: photon mediation

III. GALP-to-photon conversion in the electromagnetic field of the nucleus:

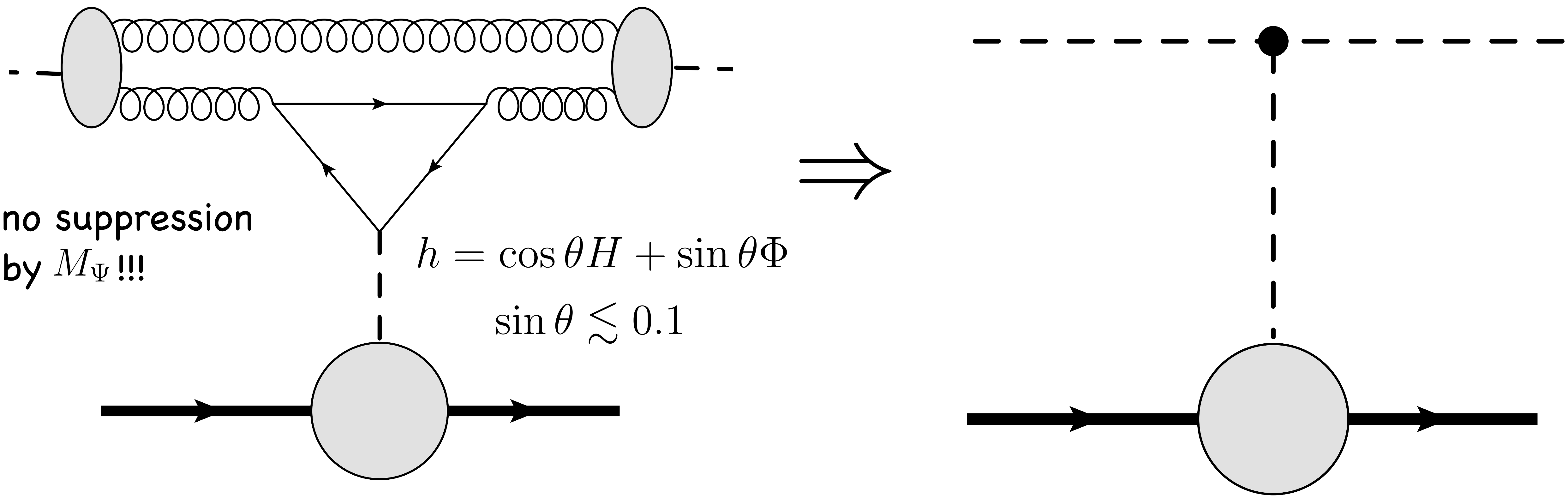


- ✓ The radiated photon takes most of the energy of the GALP but would be produced collinearly in the direction of the GALP
- ✓ Despite possible enhancement from the real photon flux in a heavy nucleus, the CS estimates for available GALP parameter space lead to hopelessly small rates for DD measurements to probe

We need to consider other mediators to possibly enhance the signal!

GALPs Direct Detection prospects: Higgs mediation

IV. Higgs mediated elastic GALP-nucleon scattering:



There are four sources of suppression of this amplitude:

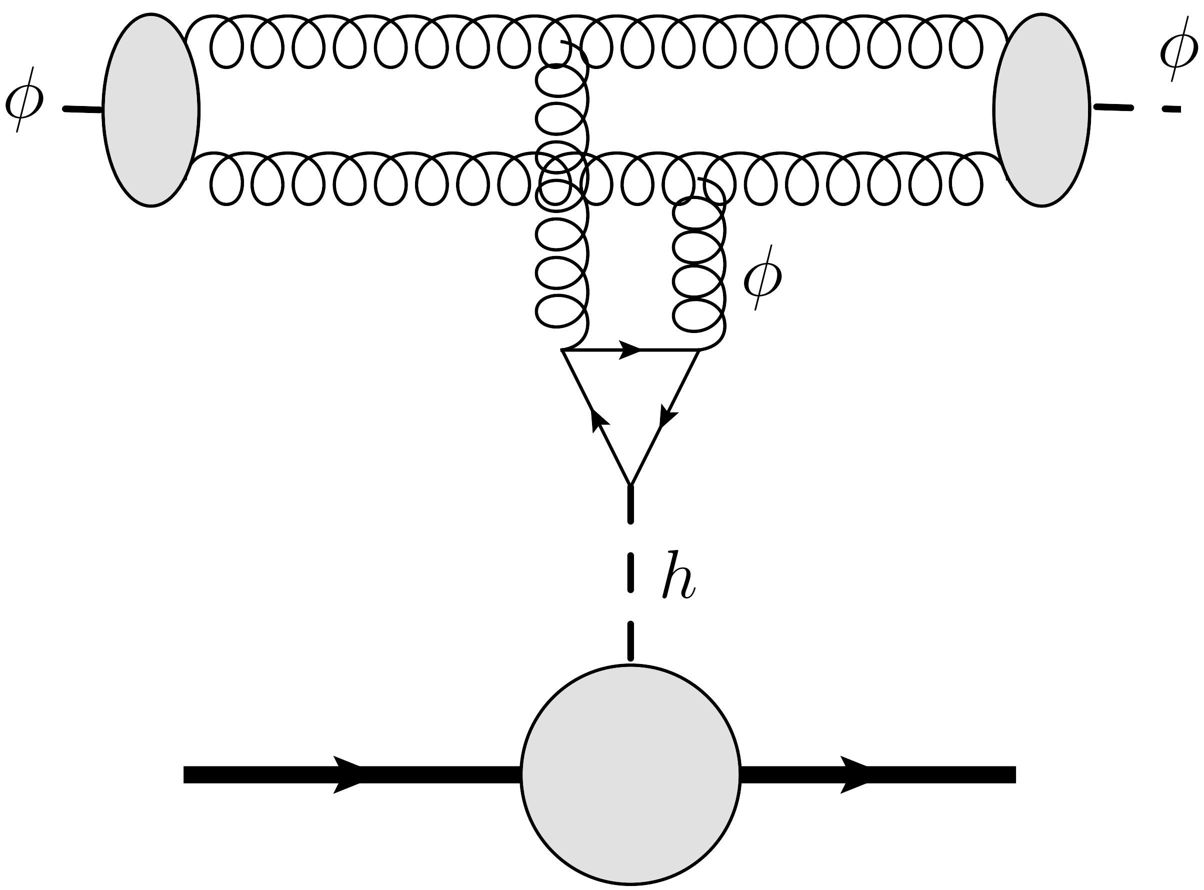
- ⇒ By the Higgs mass in the propagator
- ⇒ By SU(N) gauge coupling
- ⇒ By Higgs Yukawa coupling to the SM fermions
- ⇒ Small Higgs-singlet mixing

Potentially realistic to probe!

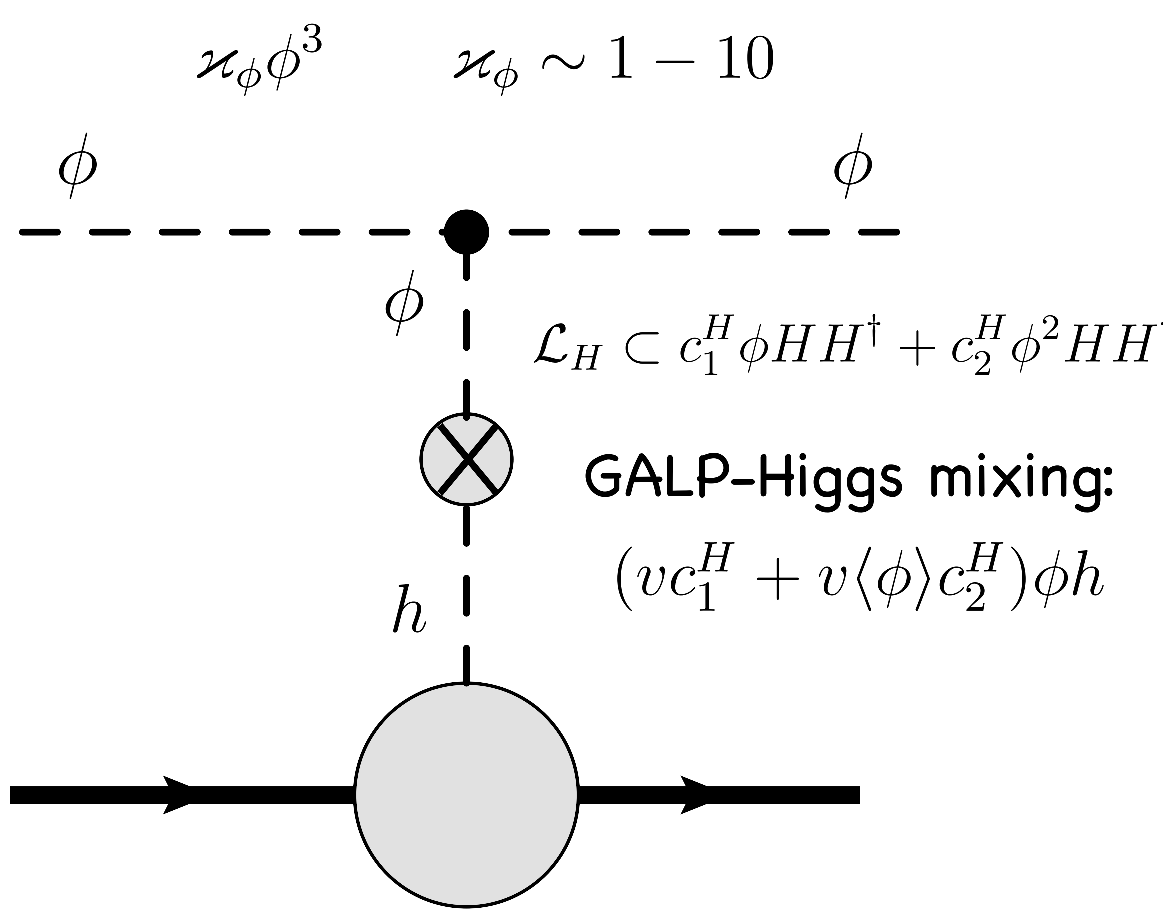
GALPs Direct Detection prospects: Higgs mediation

V. Enhanced Higgs mediated elastic GALP-nucleon scattering

- ✓ Due to strong dynamics, one could enhance the Higgs mediated scattering, by considering non-perturbative GALP-self-interaction contribution:



$\Rightarrow$

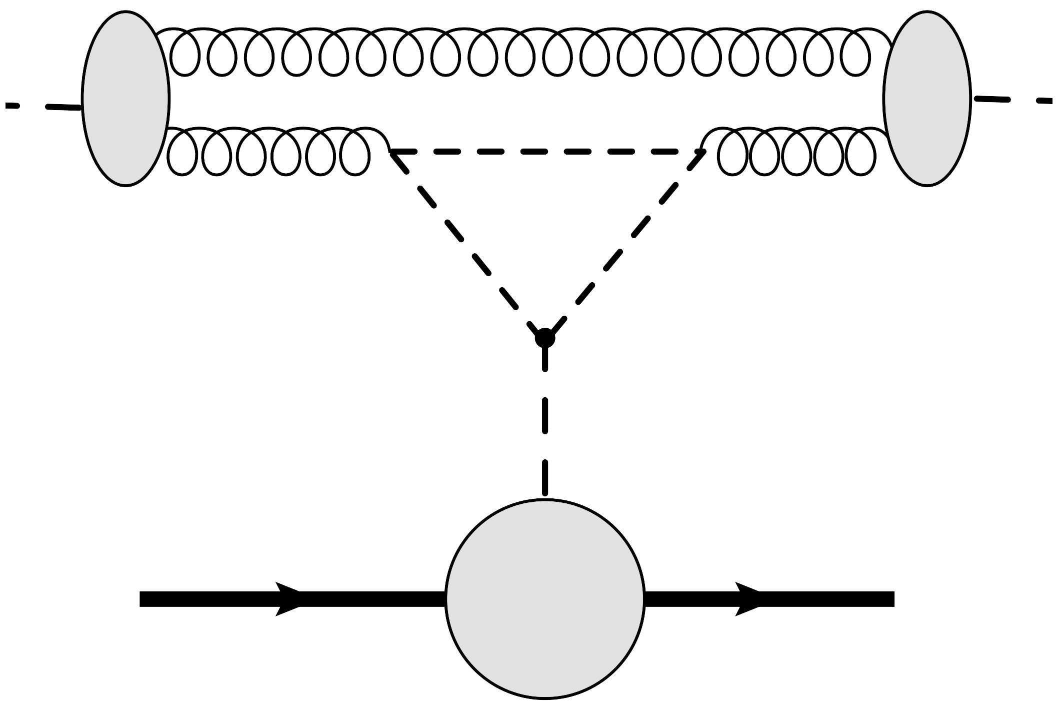


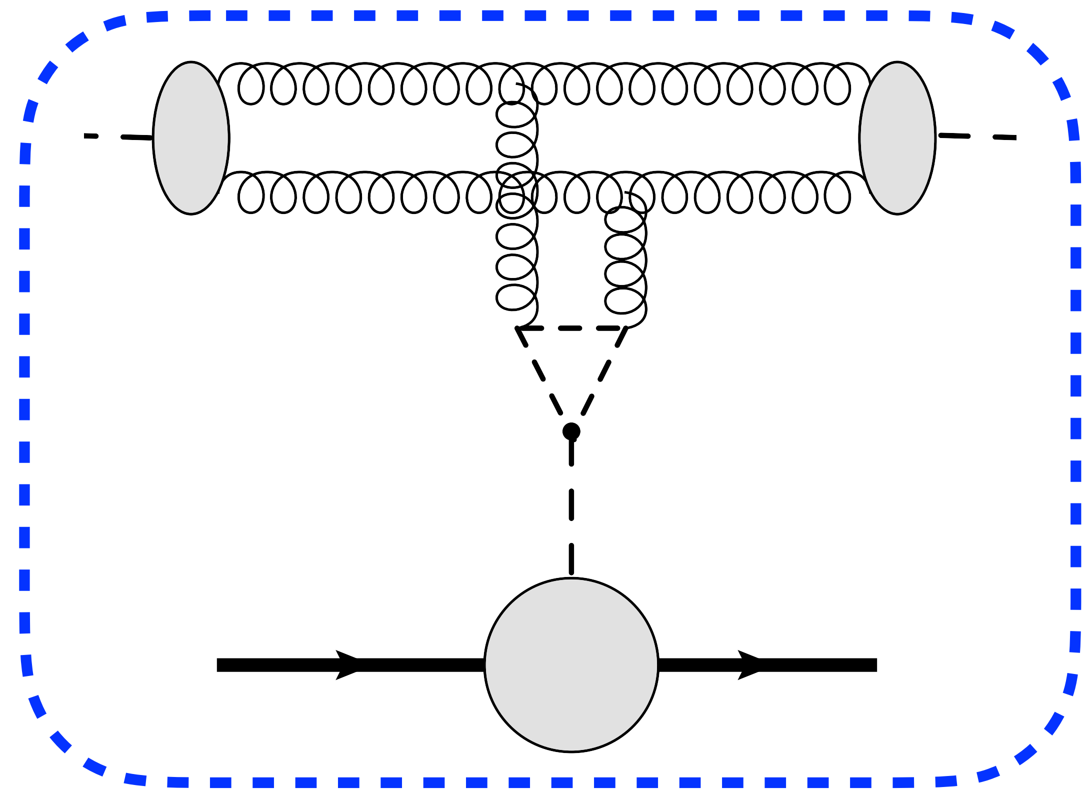
GALP self-interaction can enhance the CS by 2-3 orders of magnitude!

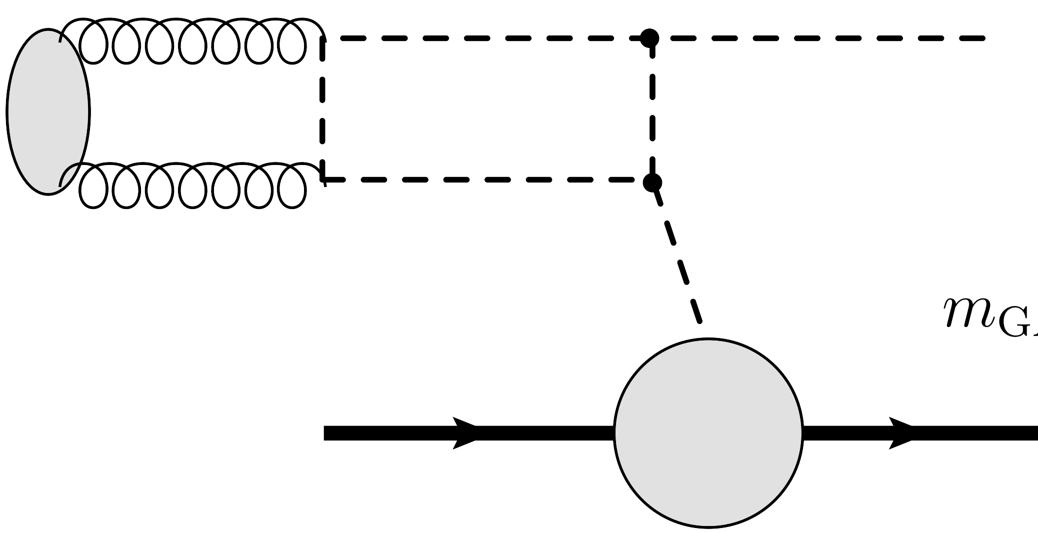
GALPs Direct Detection prospects: Higgs mediation

VI. Higgs exchange mediated by colored scalar loop

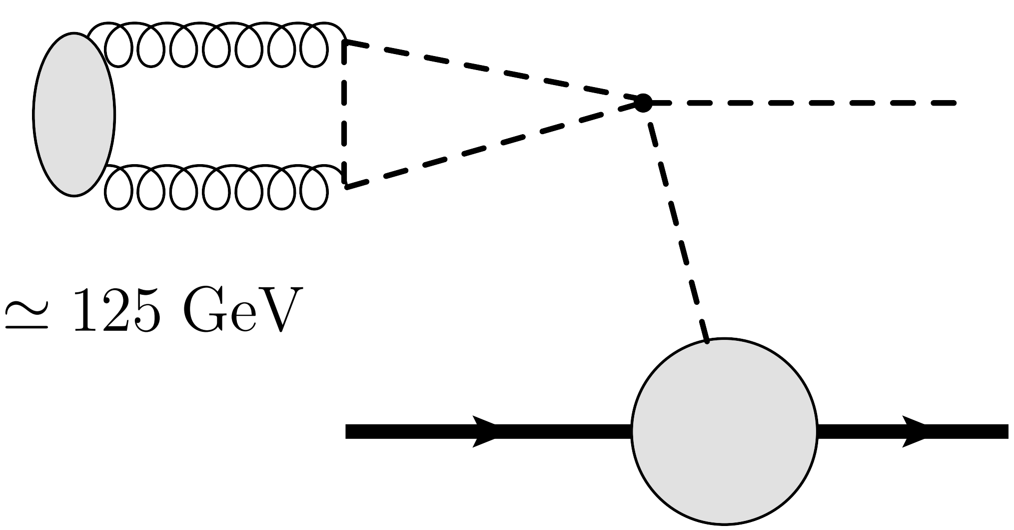
✓ Utilising a heavy dark-coloured scalar instead of the fermion the direct detection CS can be further enhanced due to HSS self-interaction, and avoiding a suppression by the mixing





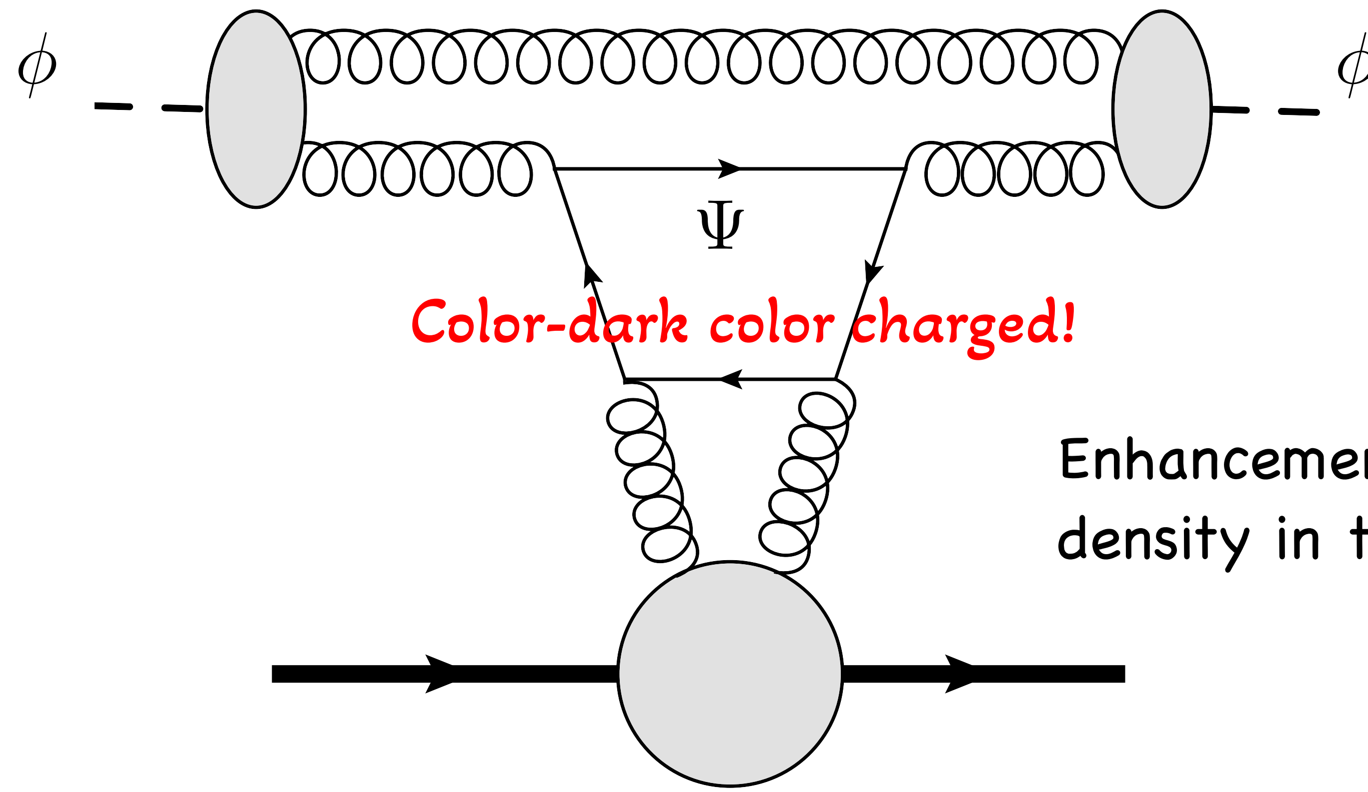


$$m_{\text{GALP}} \gtrsim m_h \simeq 125 \text{ GeV}$$



GALPs Direct Detection prospects: QCD mediation

vII. Elastic GALP-nucleon scattering with di-gluon exchange:



Enhancement due to a large gluon density in the nucleus!

The same operator drives GALP di-hadron annihilation in the Galaxy: potentially robust indirect DM detection signature!

Strong suppression of the GALP -> di-pion -> 4 photons decay channel

below the di-pion invariant mass!

Summary

- Composite DM framework naturally offers ample opportunities for particle physics, astrophysics and cosmology, both for theory and experiments

- A dark gauge sector with glueball ALPs (GALPs) feebly interacting with the SM may explain the DM abundance without spoiling other cosmological observables

- A new approach based upon the well-established thermal EFT and the existing lattice results enables one to compute the GALP relic density precisely incorporating confinement effects and non-perturbative self-interactions

- Introducing extra heavy fundamental fields (e.g. fermions, scalars) charged under both the dark gauge symmetry and the SM, or coupled to Higgs, one generates feeble effective GALP-nucleon interactions that can be, in principle, probed by direct detection experiments